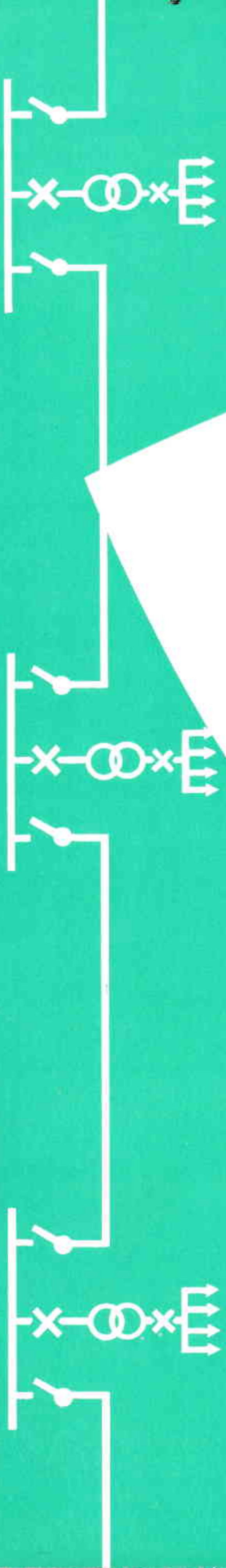

AN OUTLINE OF A.C. ELECTRICAL POWER DISTRIBUTION SYSTEMS

'ENGLISH ELECTRIC'

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'ENGLISH ELECTRIC'

AN OUTLINE OF A.C.
ELECTRICAL POWER
DISTRIBUTION
SYSTEMS

SYSTEM DESIGN

Electrical engineers are frequently called upon to design a new, or extend an existing, electrical distribution system.

This publication is an attempt to clarify some of the factors involved, and to summarise the salient features of several typical systems which can be used as a basis for almost every individual requirement.

It is useful to state the questions which an engineer must ask himself when deciding on a system to meet a new or increased demand for electrical power.

In any system design for the distribution of electrical power, it is found that due emphasis allocated to the following general factors will usually decide the basic scheme to be used. The details may then be completed by a consideration of any special requirements of the case under review.

Efficiency

The losses that will be incurred in cables or lines when transmitting power from one point to another, and also the iron and copper losses of any transformers, must be considered.

The system power factor is also a measure of efficiency and must be taken into consideration in so far as it affects the choice of cables, transformers and switchgear, and very often the size of the electricity account. However, since the connected load is the main influence governing power factor, and not the system design itself, power factor and methods of improvement will not be considered in greater detail here.

Safety

This is a property which cannot be measured in terms of capital outlay and should be a major consideration in any system design. The standard here should be good quality equipment, properly installed, regularly maintained, and operated by experienced personnel working to a well-designed set of safety rules.

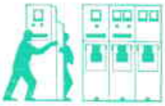
Continuity of supply

The importance to be attached to this question will be decided mainly by a consideration of the losses which may be incurred by an interruption of supply to all or part of the system. Very often the magnitude of this loss, when compared with the cost of precautionary measures, makes the latter extremely desirable. Notwithstanding this fact, however, a certain amount of "risk" can be justified, bearing in mind present day reliability of fully-tested, certified, high quality equipment.

System regulation

Consideration must be given to the voltage available at various points and how it changes with load, particularly that which is suddenly applied.

Flexibility



This is a measure of the system's ability to absorb changing load conditions such as might be occasioned by the moving of plant to a different location, or perhaps connection of additional load in the future. At the stage indicated, as 'English Electric' Switchboards incorporate a unit busbar system, it would not be necessary to interrupt the supply.

Initial cost

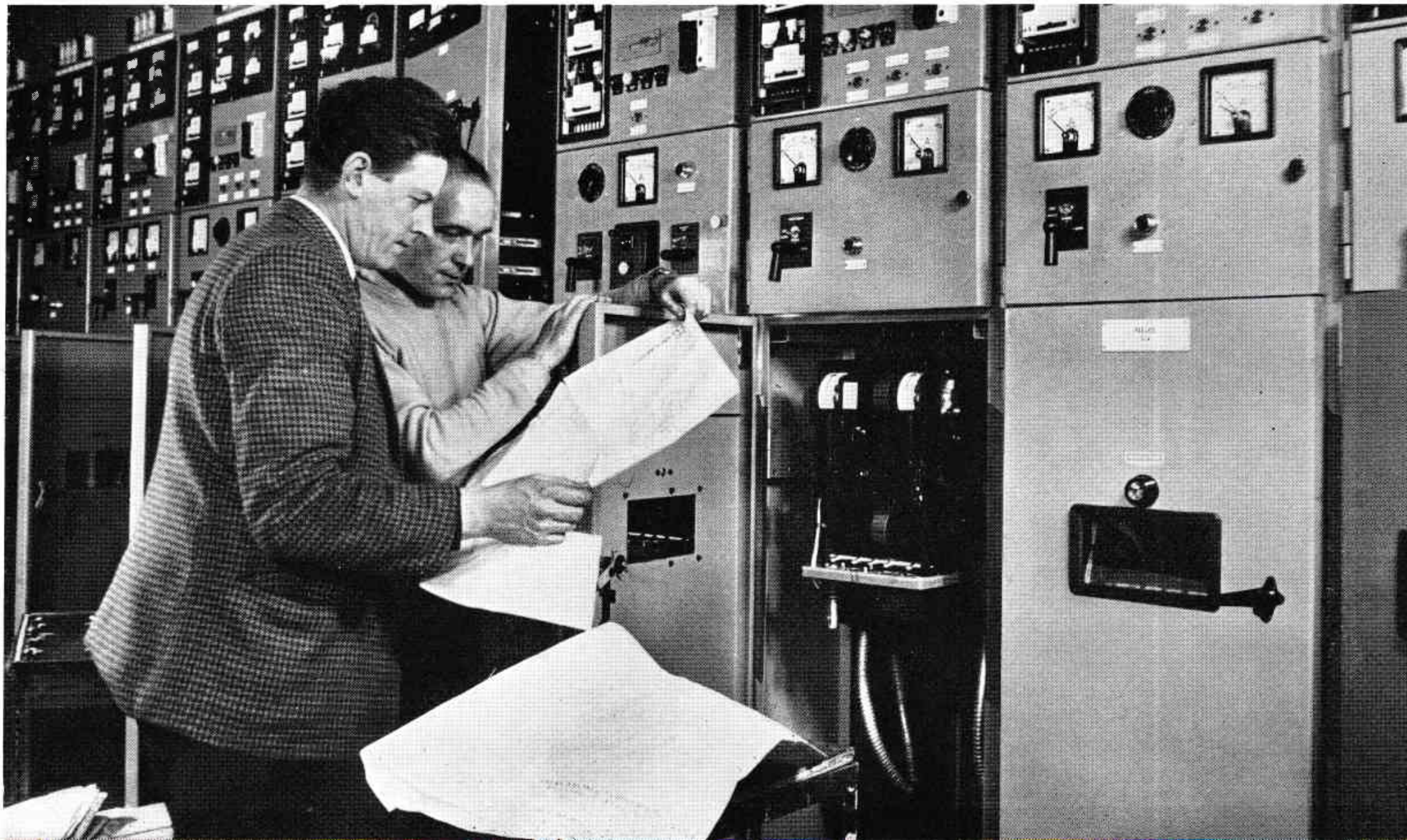
The initial capital outlay for any scheme will obviously be decided by the facilities required, but it can be safely said that the cheapest system that will transmit electrical power from one point to another does not depend entirely on first cost, and it is usually preferable to take a long term view.

Maintenance costs

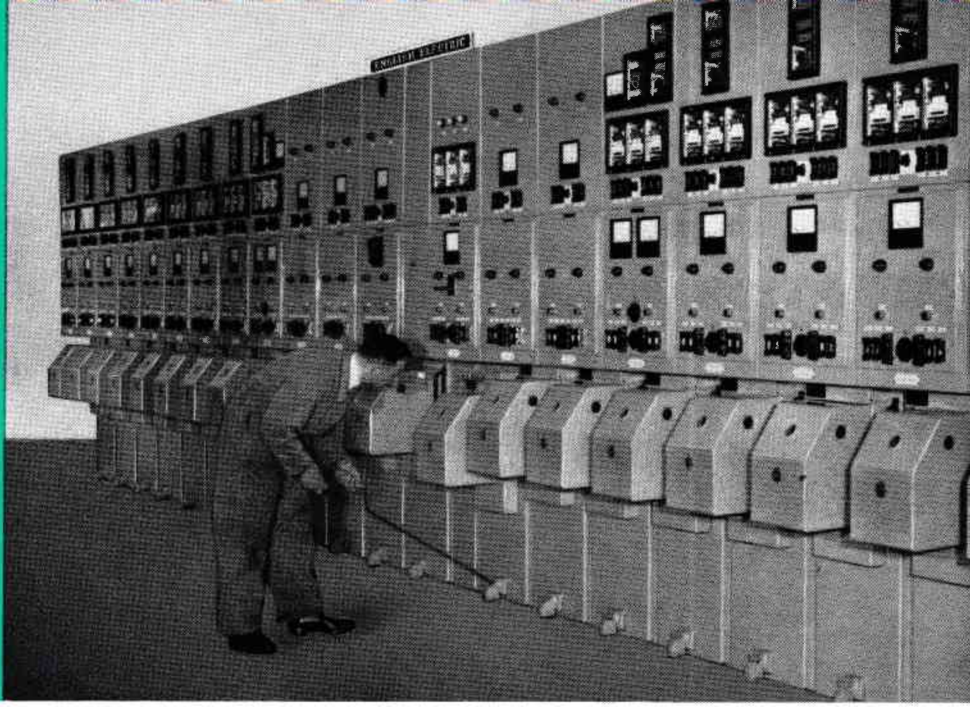
This is a very important subject and obviously cost of maintenance will depend a great deal on the quality and suitability of the equipment used. Consideration must also be given as to how a particular system design allows equipment to be isolated for inspection, test or routine maintenance, and what facilities are available for keeping the interruption of supply to a minimum.

Having established the general concept of the system required, it follows that the selection of suitable equipment will be the next consideration.

An 'English Electric' 11 kV, 350 mVA class CV compound-insulated oil-break switchboard, arranged for auto-reclose, undergoing test.



CHOICE OF SWITCHGEAR



There may be many opinions regarding switchgear requirements, but it is certain that the main duties listed below are fundamental.

1. The control of a distribution system and connected equipment by normal switching functions. A consideration of these determines the normal current and voltage rating of the switchgear.
2. The provision of a suitable centre for the accommodation of metering, instrumentation and relay equipment, and these factors to some degree govern the layout of the switchgear.
3. Protection of the system and connected equipment by automatic operation under fault conditions. The value of fault power available at any particular part of the system will thus determine the MVA breaking-capacity of the switchgear, and a knowledge of the calculations for the assessment of power flow under fault conditions is, therefore, necessary in order that the correct specification shall be applied to the switchgear according to its position in the system.

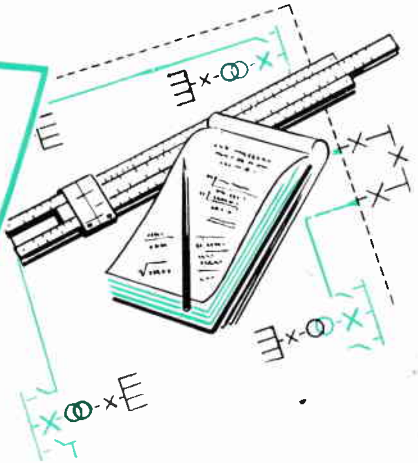
With a three-phase alternating-current system, the British practice is to specify circuit-breaker breaking-capacities in terms of the system voltage and the fault power to be interrupted under symmetrical fault conditions, namely a short-circuit between all three phases. Therefore, if a circuit-breaker is certified for 250 MVA at 11,000 volts, this means that it is suitable for use on an 11 kV system where the symmetrical fault level does not exceed 250 MVA as calculated in the following section.

It will be obvious that in addition to breaking fault current, a circuit-breaker must be capable of withstanding closure on to a fault, and will thus have a rated making-capacity, which should take into account the full initial transient current, since this is considerably more than the steady-state value which is used when calculating symmetrical breaking-capacities.

Unless it is intended that, regardless of its position in the system, the circuit-breaker should operate immediately fault current passes, it will also have a short-time current rating, which specifies the length of time for which it is capable of carrying the fault current.

Technical information, showing typical values of breaking and making capacities, and short-time current ratings for 'English Electric' circuit-breakers, can be supplied on request.

THE CALCULATION OF SYMMETRICAL SHORT-CIRCUITS



Percentage Reactance method

Three-phase faults only are considered in the following calculations, and the study is limited to the calculation of symmetrical A.C. short-circuit currents or fault-power, so that the initial, larger value of current resulting from a transient D.C. component is ignored.

The value of symmetrical A.C. fault-current to be calculated, and partially defined above, is, for most conventional distribution systems, the maximum provoked by any type of fault, but systems with solidly-earthed alternators or zig-zag connected transformers may incur even larger values of earth fault current.

The calculations use line currents and phase-to-neutral voltages. If delta windings are found on the system to be examined the phase-to-neutral voltage is a theoretical quantity but the calculations will not be affected.

Simple Ohmic method

Considering a three-phase supply source, e.g., an alternator, with phase-to-phase voltage V, and full load current I_f, then:

Alternator full load kVA is:

$$\frac{\sqrt{3}.V.I_f}{1000} \text{ kVA} \qquad ..(1)$$

If the alternator short-circuit reactance is X_p ohms, (for most practical purposes the source resistance can be assumed to be negligible) the symmetrical short-circuit current per phase, I_s, caused by a three-phase fault, will be:—

$$I_s = \frac{\frac{V}{\sqrt{3}}}{X_p} = \frac{V}{\sqrt{3}.X_p} \qquad ..(2)$$

From equation 2 the short-circuit volt-amps per phase, i.e., phase-to-neutral voltage multiplied by I_s, is given by the expression:—

$$\frac{V}{\sqrt{3}} \times \frac{V}{\sqrt{3}.X_p} = \frac{V^2}{3.X_p}$$

Therefore, the total three-phase short-circuit kVA delivered by the alternator will be:—

$$3 \times \frac{V^2}{3.X_p} \times \frac{1}{1000} = \frac{V^2}{X_p.1000} \text{ kVA s.c.} \qquad ..(3)$$

The ohmic method can be applied to systems rather more complicated than the simple example used above, but usually it will be found more convenient to use the ‘percentage impedance’ or ‘percentage reactance’ method.

Percentage Impedance or Reactance method

The data plate on a power transformer will give, inter alia, the transformer impedance voltage expressed as a percentage. This figure is often loosely referred to as the transformer’s ‘percentage impedance’.

The meaning of this term becomes clear if the method of measuring percentage impedance is considered. One winding of a two winding transformer is short-circuited whilst a variable voltage is applied to the other winding and adjusted so that normal full load current is produced in the short-circuited winding. The voltage so determined, expressed as a percentage of the normal voltage of the winding to which the voltage is applied, is the percentage impedance voltage; commonly, but, inaccurately, known as the percentage impedance. The common term will be used in the following notes.

If it is known that a transformer has a percentage impedance of 5%, it now follows that if the secondary winding is short-circuited, 5% of the normal primary voltage applied to the primary winding will induce normal full load current in the secondary. Now if normal primary voltage is applied to the primary, then the current in the short-circuited secondary will be:—

$$I_{fL} \times \frac{100}{5}$$

Where I_{fL}=secondary full-load current. Consequently, if a transformer having an impedance of 5% is supplied from a power source of negligible impedance then a short-circuit across the secondary terminals will cause a secondary current of 20 times normal full-load.

At this stage in this study of short-circuit calculations by the percentage impedance method a value of fault current only has been established, but if in the expression above the full-load kVA of the secondary winding is substituted for the full-load current, the magnitude of the short-circuit will be expressed as fault power or fault kVA. Therefore assuming negligible power source impedance, the fault power arising from a three-phase short-circuit on a transformer secondary winding will be:—

$$\left(\text{kVA}_{fL} \times \frac{100}{Z}\right) \text{kVA} \qquad ..(4)$$

Where kVA_{fL} is the transformer full load rating and Z is the percentage impedance of the transformer.

Usually the resistance of A.C. power systems is negligible as compared to reactance, therefore in many instances the values of percentage impedance and percentage reactance may be interchanged. This may not be permissible if appreciable lengths of cable or overhead line are involved since such systems may have resistance values approaching the value of reactance and in these cases the percentage impedance should be used, derived from the formula:—

$$Z\% = \sqrt{(X\%)^2 + (R\%)^2}$$

The use of kVA as a base in these calculations is convenient, since knowledge of system voltage is not required to determine fault kVA. This is useful for example if considering the effect of two transformers in series, because (assuming a power source of negligible impedance) the percentage reactance of the two transformers may be added arithmetically provided they are on the same base of kVA.

To convert the percentage reactance of a transformer (or other plant or apparatus) from its normal base kVA, which in this case is the full-load kVA of the transformer, to the new selected common base, the following formula should be used:—

New percentage reactance

$$= \text{Old percentage reactance} \times \frac{\text{New Base}}{\text{Old Base}} \qquad ..(5)$$

Proceeding with the example, the two transformers selected are—

(a) 1000 kVA with a percentage reactance of 5%.

(b) 750 kVA with a percentage reactance of 4·5%.

and it will be necessary to convert these percentage reactances to a common base. In choosing the rating of the larger transformer as the common base, the stated percentage reactance of (a) will remain unchanged, whereas that of (b) must be converted to a new value on the chosen base of 1000 kVA. Thus, from (5):—

$$4{\cdot}5\% \times \frac{1000}{750} = 6\%$$

and the short-circuit power which can be transmitted through the two transformers in series will be:—

$$1000 \times \frac{100}{5+6} = 9080 \text{ kVA}$$

In this form of calculation voltage level is not of interest unless the value of short-circuit current is required to be known. Pursuing the example the voltage ratios of the two transformers might be:—

(a) 1000 kVA — 11 kV/3·3 kV

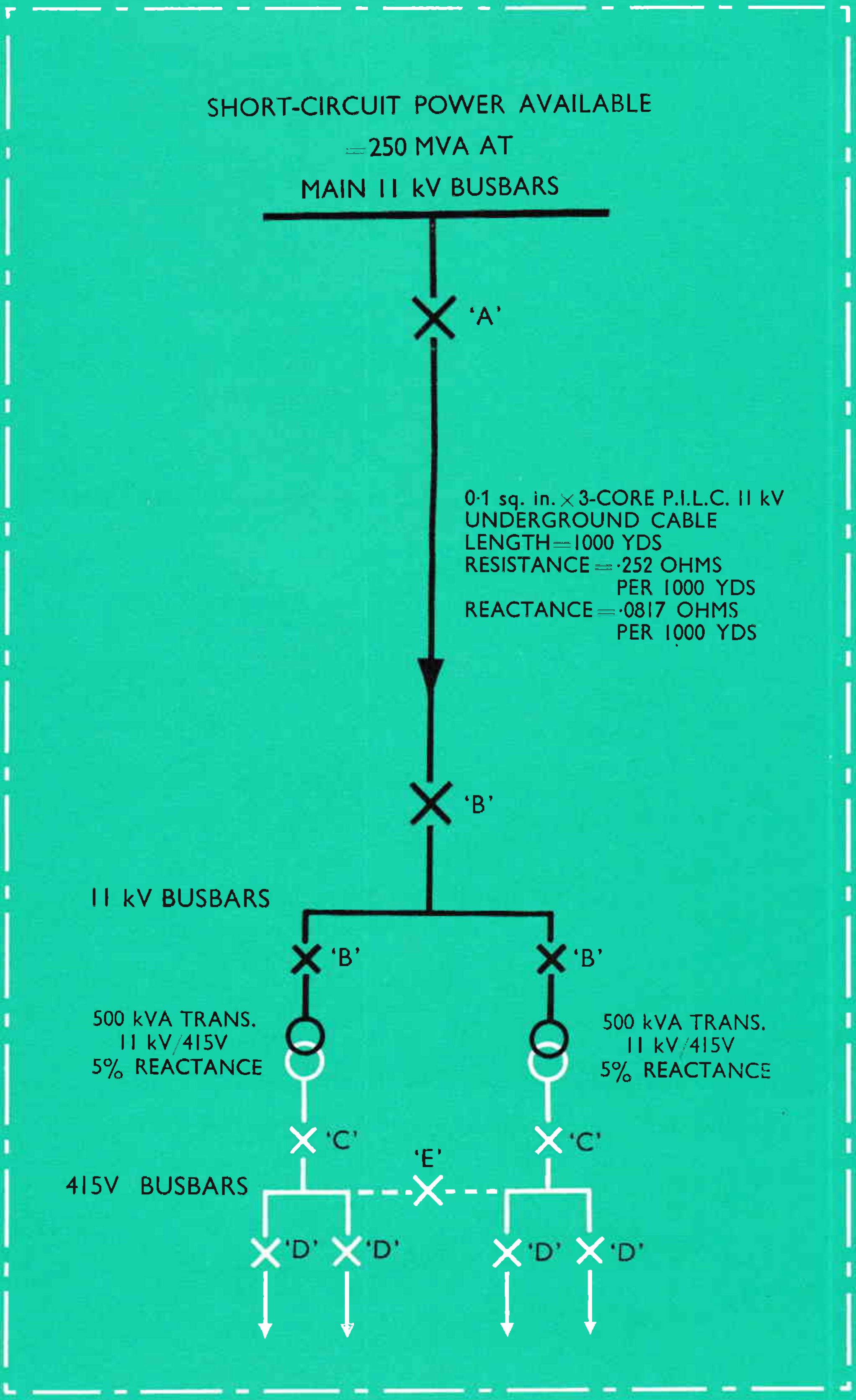
(b) 750 kVA — 3·3 kV/433 V

Irrespective of these voltage levels the value of 9080 kVA fault level remains unchanged and as it is present on the 433 volt system, the short-circuit current at that level is:—

$$\frac{9080 \times 1000}{\sqrt{3} \times 433} = 12{,}100 \text{ amps.}$$

Open-circuit voltage should be used in these calculations and not the 'on-load' voltage; 433 volts is the normal open-circuit voltage of a transformer winding feeding a 415 volt system. The error caused by using the 'no-load' figure is not usually serious.

Calculations involving apparatus other than transformers (e.g., alternators or reactors) will follow the same pattern. The sub-transient react-



SYMBOLS

✕ Automatic circuit-breaker

◎ Transformer

→ Direction of normal load current

ance of alternators is usually the percentage reactance value to be used.

Source Impedance or Reactance

In the previous calculations it has been assumed that the power source is of negligible impedance. This is not always the case and frequently has to be taken into account.

For example a 5 MVA transformer with an impedance of 8% may be connected to an 11 kV supply system having a fault level of 250 MVA.

Ignoring the source impedance the fault level on the secondary of the transformer is:—

$$5 \text{ MVA} \times \frac{100}{8} = 62{\cdot}5 \text{ MVA}$$

(Note that these calculations may use MVA in place of kVA provided the same unit is used throughout).

This calculation, which ignored power source impedance, used the transformer rated MVA as the base since the percentage reactance of the transformer (8%) related to the transformer rated MVA. Therefore, the source must be expressed as percentage reactance on the same base of 5 MVA.

To simplify this conversion it may be conveniently assumed that the power source is replaced by a simple device (e.g., a transformer), which has a rating equivalent to the base MVA being used for the calculation, and a percentage reactance to give (in this case) a fault level of 250 MVA.

Formula (4) gives the following equation (the impedance being considered fully reactive):—

$$\text{MVA}_{\text{fL}} \times \frac{100}{X_s} = \text{MVA}_{\text{s.c.}}$$

$$\text{i.e., } X_s = \frac{\text{MVA}_{\text{fL}} \times 100}{\text{MVA}_{\text{s.c.}}} \qquad ..(6)$$

Where X_s = Percentage reactance of source
MVA_{fL} = Base MVA
$\text{MVA}_{\text{s.c.}}$ = Fault level of source

In the example $X_s\%$ will be $\frac{5}{250} \times 100\% = 2\%$

The true fault level in the example considered will, therefore, be:—

$$5 \times \frac{100}{8+2} \text{ MVA} = 50 \text{ MVA}$$

This example demonstrates that source impedance may have an appreciable effect and should not be ignored.

Cable Impedance

Cable impedance (and sometimes that of other apparatus) is usually given in ohms whereas it may be required to express it as percentage reactance or percentage resistance on a chosen base of kVA or MVA for calculation purposes. For this conversion it is necessary to know the voltage level at which the cable is operating.

The approach to this problem is as follows:—

Suppose the chosen base of calculation in kVA is P, then the equivalent base current at a given voltage level is—

$$\frac{P \times 10^3}{\sqrt{3} \times V}$$

where 'V' is the system line-to-line voltage of the cable.

If the resistance and reactance of the cable are r ohms and x ohms respectively then the resistive volt drop per line will be:—

$$\frac{P \times 10^3 \times r}{\sqrt{3} \times V} \text{ Volts}$$

This volt drop expressed as a percentage of phase-neutral voltage is—

$$\frac{P \times 10^3 \times r}{\sqrt{3} \times V} \times \frac{\sqrt{3}}{V} \times 100$$

$$= \frac{P \times 10^3 \times r \times 100}{V^2}$$

$$= \frac{P \times r \times 10^5}{V^2} = \text{percentage resistance for base P} \qquad ..(7)$$

Similarly, the percentage reactance is—

$$\frac{P \times x \times 10^5}{V^2} \qquad ..(8)$$

Where P = base kVA
x = reactance in ohms
r = resistance in ohms
V = line-to-line potential in volts

Example of calculations

Consider the system shown on page 9. To calculate the fault level at various points in the system, it is necessary first to choose a base of calculation. This is quite arbitrary and will not affect the results. Since there are two transformers rated at 500 kVA, it is convenient to choose this value as a base.

Each item of the system is considered separately as follows:—

Power Source

The fault level of the source is given as 250 MVA which using equation (6) is equivalent to:—

$$\frac{0{\cdot}5 \times 100}{250} = 0{\cdot}2\% \text{ reactance on a base of } 500 \text{ kVA } (0{\cdot}5 \text{ MVA})$$

(It is assumed that the source impedance is entirely reactive).

Cable

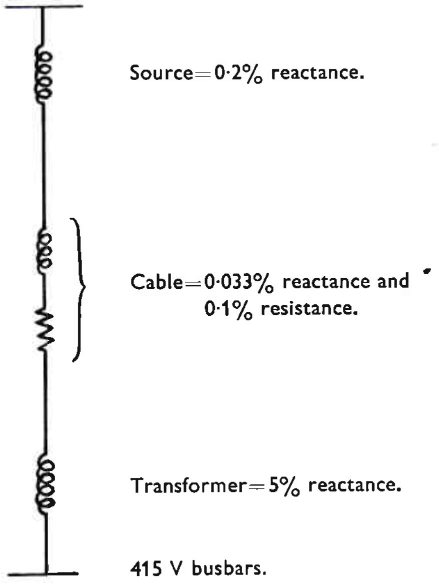
Using equation (7), the percentage resistance on a base of 500 kVA is:—

$$\frac{500 \times 0{\cdot}252 \times 10^5}{11{,}000^2} = 0{\cdot}1\%$$

similarly, the percentage reactance is:—

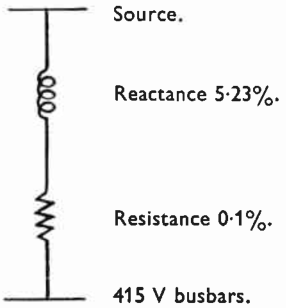
$$\frac{500 \times 0{\cdot}082 \times 10^5}{11{,}000^2} = 0{\cdot}034\%$$

An equivalent diagram can now be drawn. Assuming first that the bus-section circuit-breaker 'E' is open, the impedances from the source to circuit-breakers 'C' and 'D' can be represented:—


Source=0·2% reactance.
Cable=0·033% reactance and 0·1% resistance.
Transformer=5% reactance.
415 V busbars.

Four-panel CV switchboard in a substation of the South of Scotland Electricity Board.

By adding the reactances together, the diagram simplifies to:—

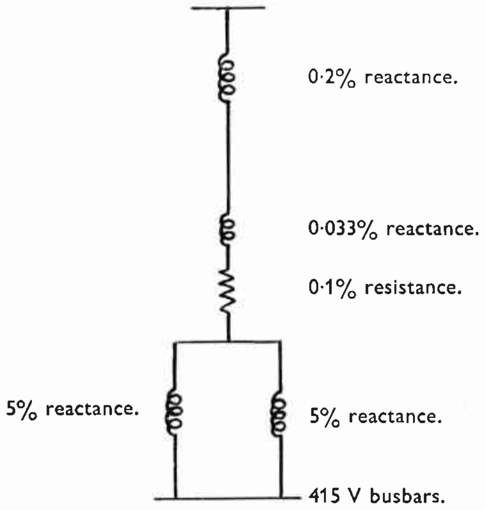


The total impedance is therefore $\sqrt{5{\cdot}23^2 + 0{\cdot}1^2}$ which is, to the second decimal place, 5·23 since the resistance value calculated proves negligible.

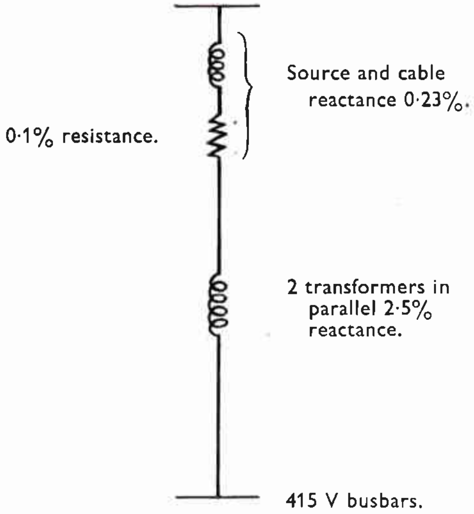
The fault level at circuit-breakers 'C' and 'D' whilst the bus section circuit-breaker 'E' is open, is:—

$$500 \times \frac{100}{5{\cdot}23} = 9{,}570 \text{ kVA or } 9{\cdot}57 \text{ MVA}$$

Considering conditions with the bus-section circuit-breaker 'E' closed, the equivalent diagram would be:—



Which simplifies to:—


Source and cable reactance 0·23%.
0·1% resistance.
2 transformers in parallel 2·5% reactance.
415 V busbars.

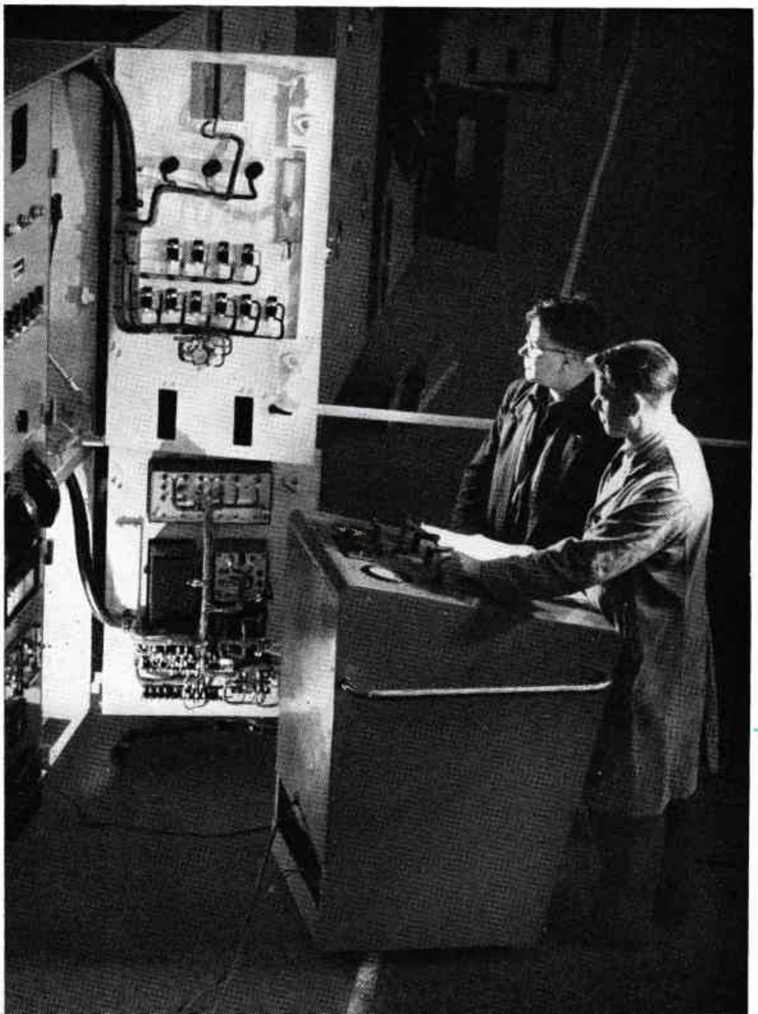
The total impedance from the source to the 415 V busbars is now:—

$\sqrt{(2{\cdot}5 + 0{\cdot}23)^2 + 0{\cdot}1^2} = 2{\cdot}73\%$

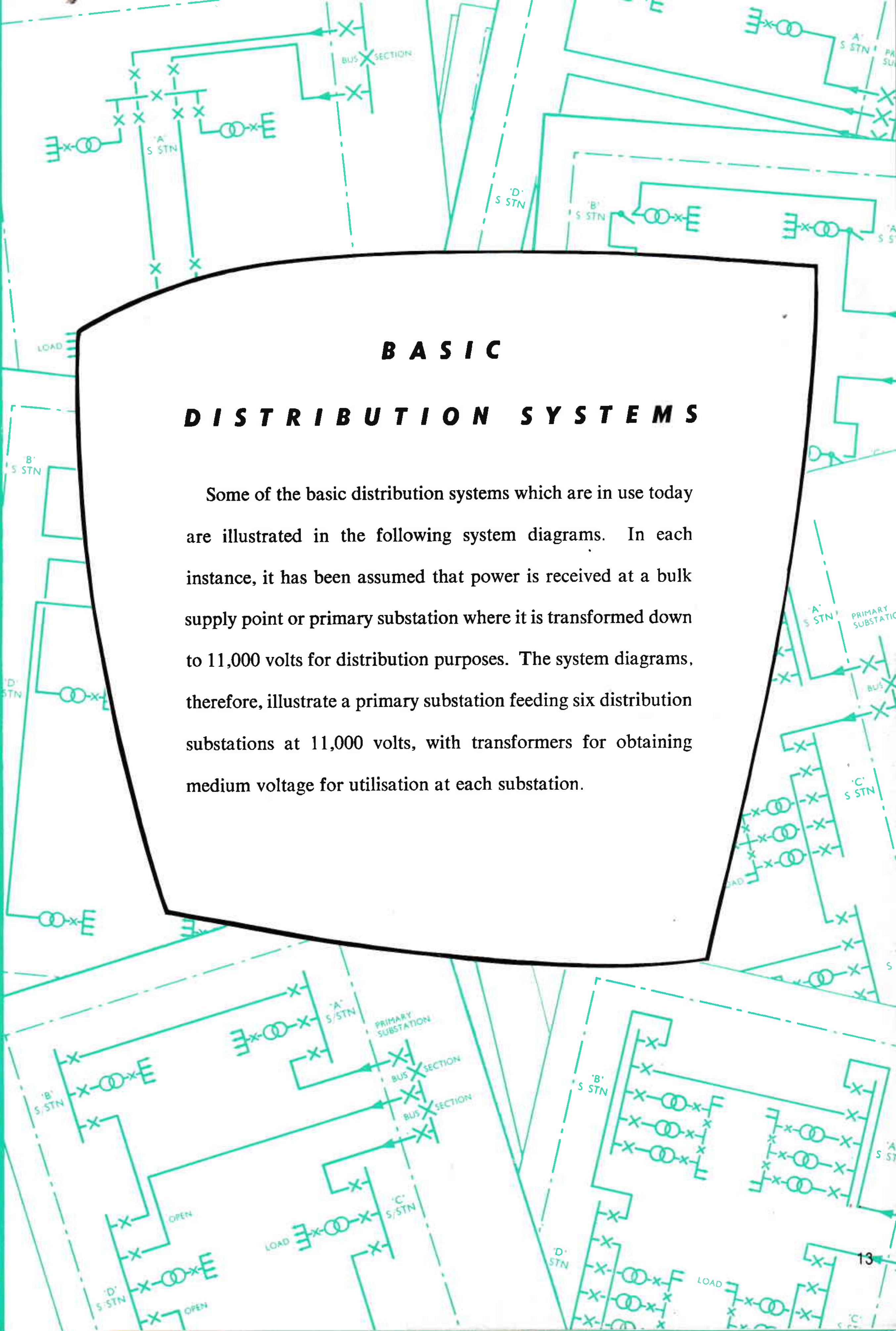
(again the resistance has negligible effect).
and the fault level is:—

$$500 \times \frac{100}{2{\cdot}73} = 18{,}300 \text{ kVA or } 18{\cdot}3 \text{ MVA}$$

It should be noted that, due to the source impedance, the L.V. fault level with two transformers in parallel is not twice the fault level available from one transformer. This difference becomes more pronounced the higher the source impedance, i.e., for lower H.V. fault level.



440V, 26MVA air circuit-breaker switchboard for Calder Hall—Britain's first atomic power station—under test at Liverpool Works.



BASIC DISTRIBUTION SYSTEMS

Some of the basic distribution systems which are in use today are illustrated in the following system diagrams. In each instance, it has been assumed that power is received at a bulk supply point or primary substation where it is transformed down to 11,000 volts for distribution purposes. The system diagrams, therefore, illustrate a primary substation feeding six distribution substations at 11,000 volts, with transformers for obtaining medium voltage for utilisation at each substation.

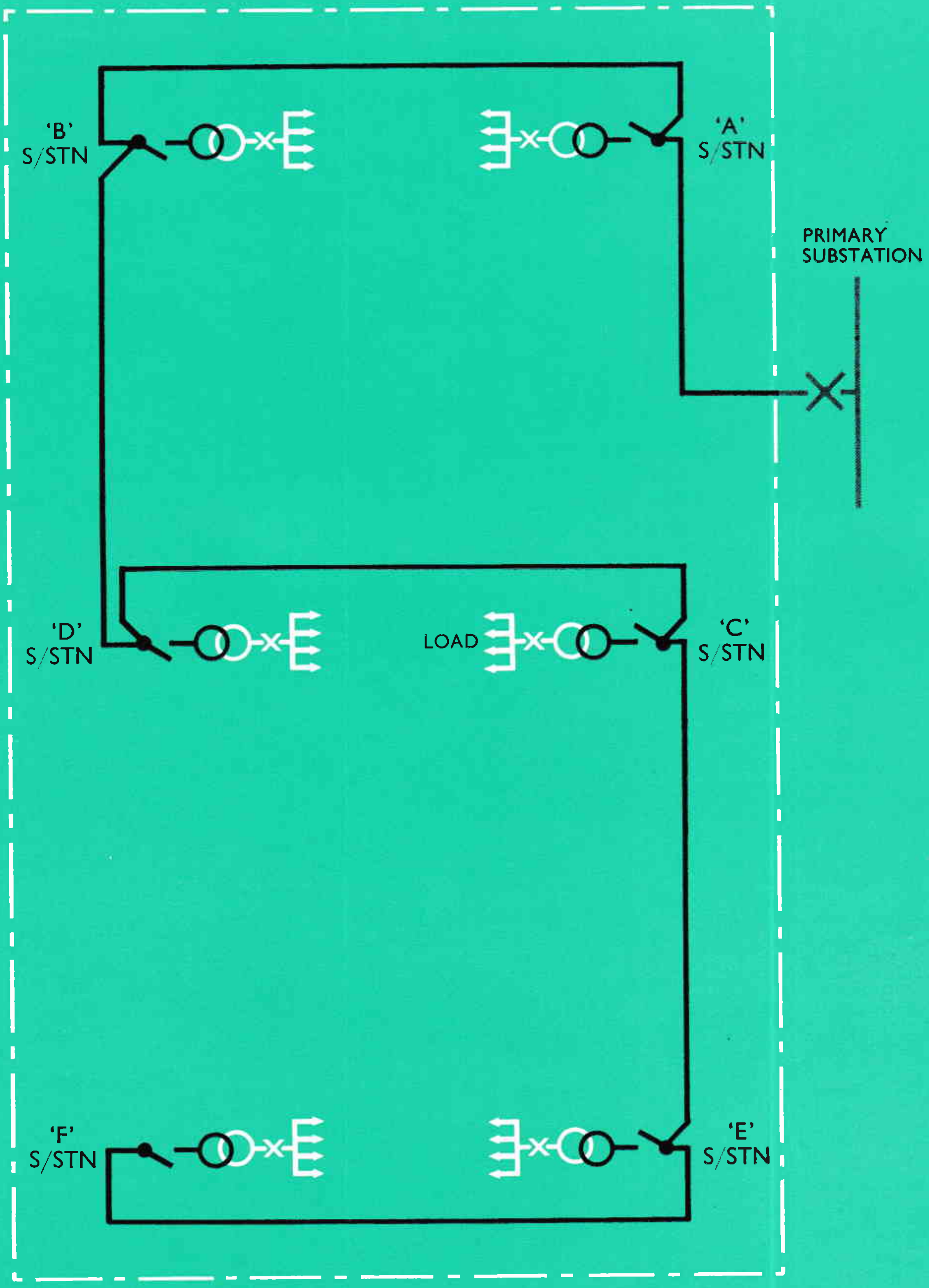
SYSTEM No. 1

This is an example of a system which has a low initial cost, being a primary substation feeding six distribution substations 'A', 'B', 'C', 'D', 'E' and 'F' all on one feeder, say at 11 kV, controlled by one automatic circuit-breaker. Various transformers for obtaining medium voltage are controlled by a fault making, load breaking oil switch, with the output from the secondary or medium voltage side of the transformer controlled by an automatic circuit-breaker, fuse switch, or isolator.

Any individual transformer or medium voltage switchboard can be isolated for inspection and maintenance without interrupting supply to the other five substations.

A fault on any part of the cable, or on any other transformers, will result in a complete loss of supply to all the system, since the only automatic circuit-breaker used in this arrangement is at the primary substation. Under cable break-down conditions supply cannot be resumed until the fault is located and repaired, but a faulty transformer can be isolated and supply restored to the other five substations.

OLX oil circuit-breaker switchboard at Whitwood Colliery, National Coal Board, North Eastern Division.



System 1

SYMBOLS

× Automatic circuit-breaker

Fault making, load breaking oil switch

Transformer

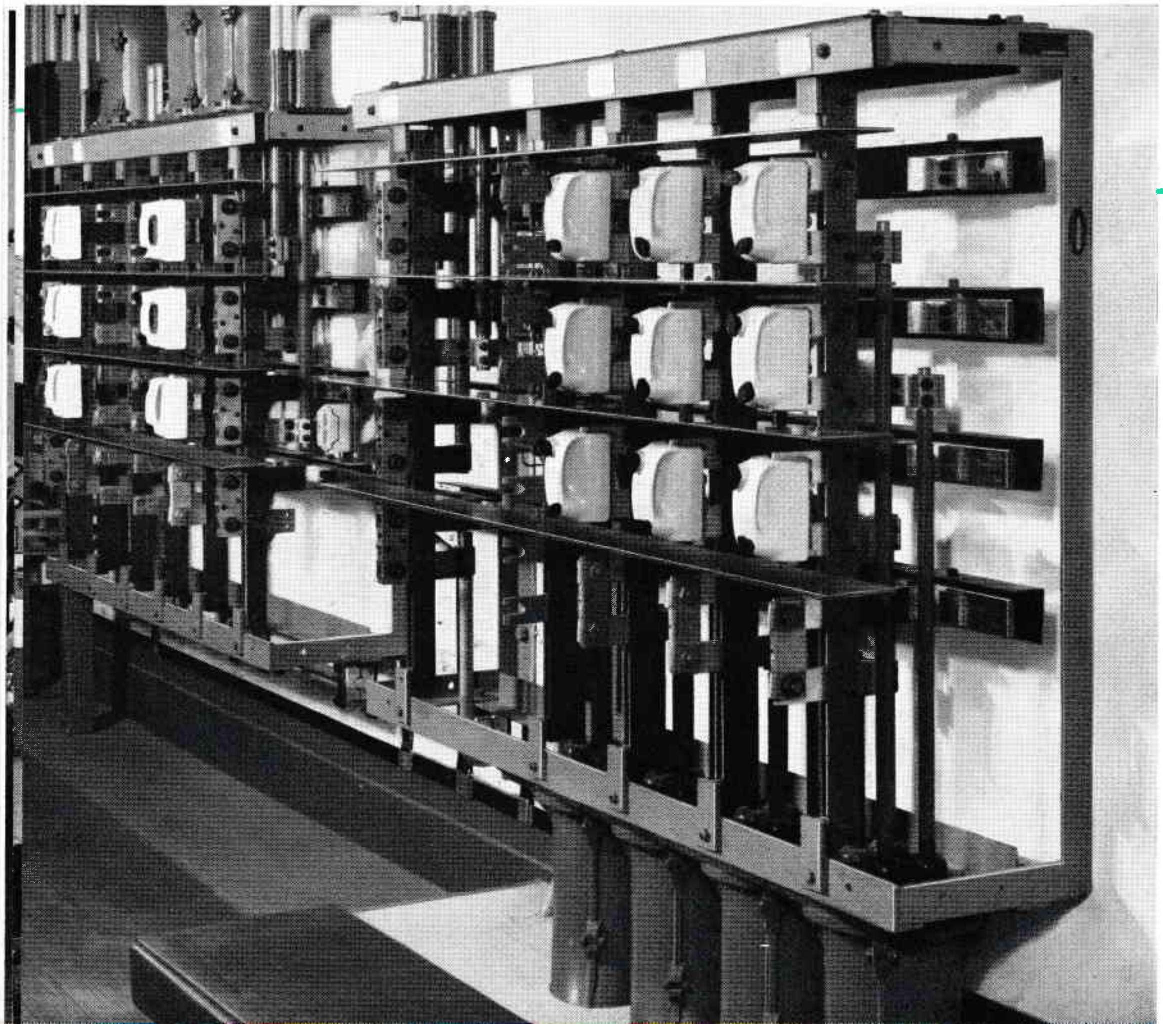
→ Direction of normal load current

SYSTEM No. 2

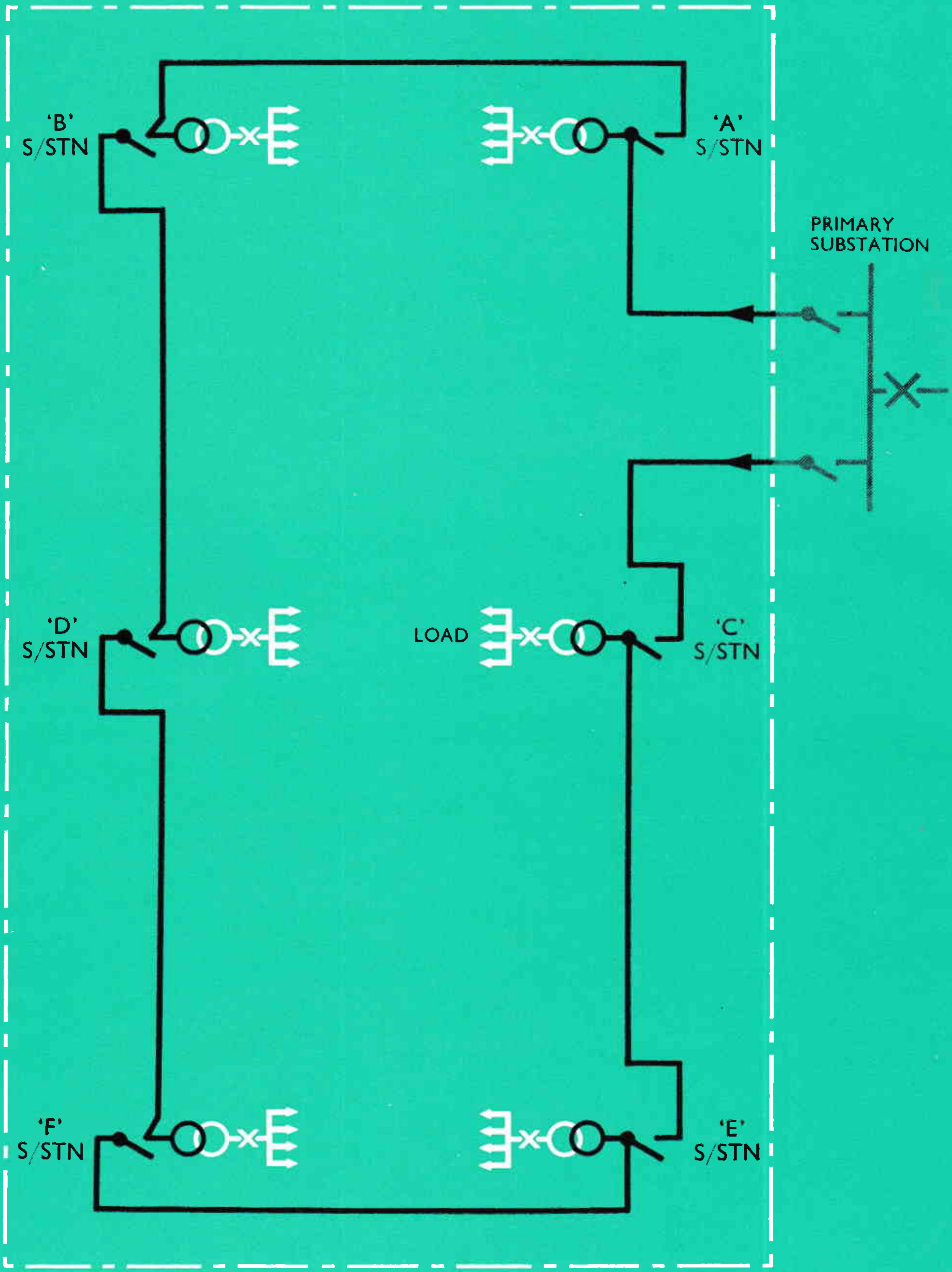
This is very similar to System No. 1, except that two additional oil switches are used in the primary substation, being controlled by one automatic circuit-breaker with the feeder taken to the six substations in the form of a ring.

Any individual transformer or medium voltage switchboard can be isolated for inspection and maintenance without interrupting supply to the other five substations.

A fault on any part of the cable, or on any of the transformers, will result in a complete loss of supply to all the system, but the fault can be isolated and supply completely restored to all except one substation, unless the faulty section is that between the primary substation and 'C' substation, in which case the section can be isolated and the supply completely restored to all six distribution substations.



CJ46 substation fuse boards at Television House—Headquarters of the Independent Television Authority.


'B'
S/STN
'A'
S/STN
PRIMARY
SUBSTATION
'D'
S/STN
LOAD
'C'
S/STN
'F'
S/STN
'E'
S/STN

System 2

SYSTEM No. 3

In this system each substation has its own feeder and associated automatic circuit-breaker in the primary substation, where there is also a bus-section switch as a means of sectionalising the busbars.

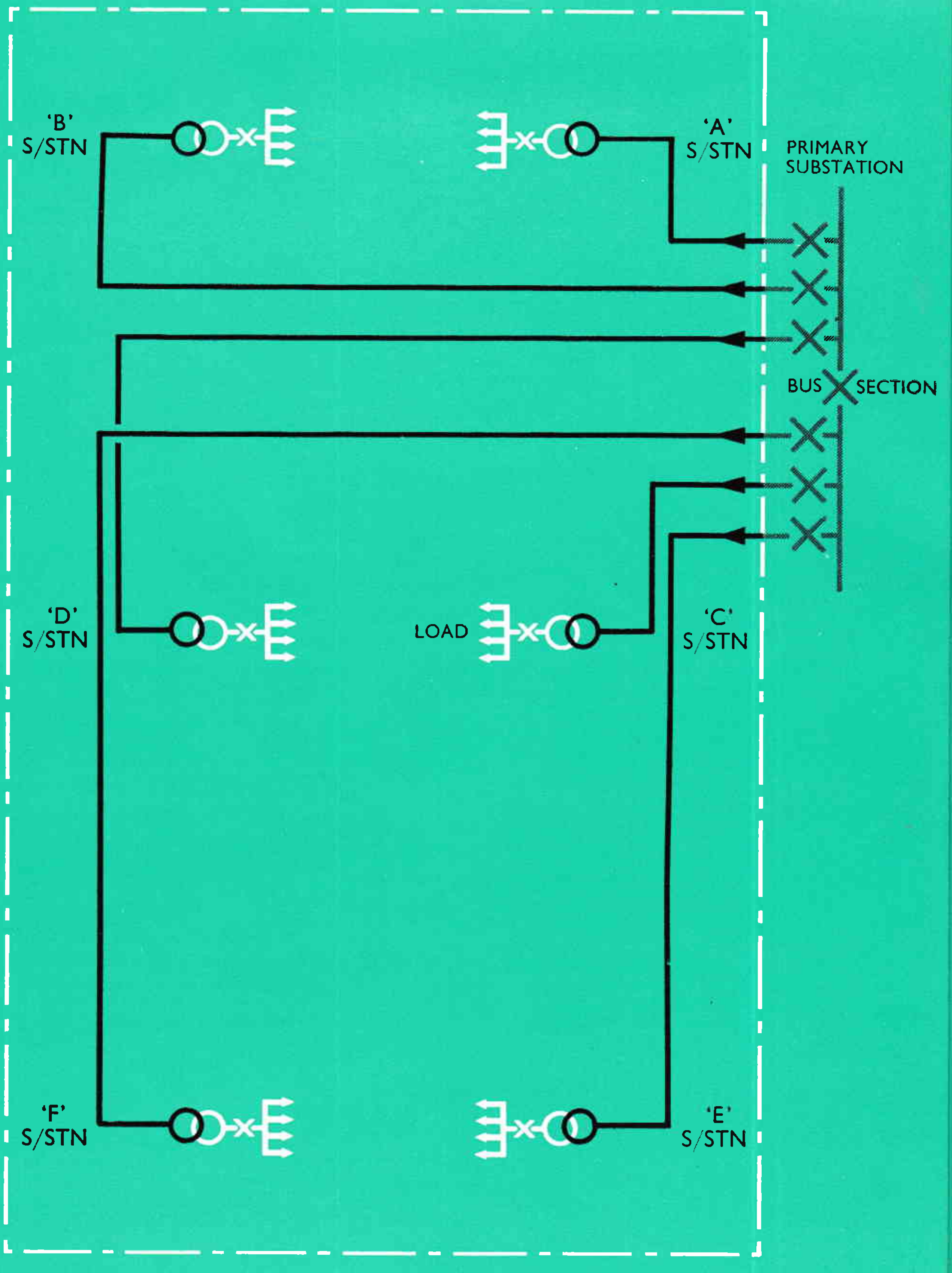
Any individual transformer or medium voltage switchboard can be isolated for inspection and maintenance without interrupting supply to the other five substations.

A cable or transformer fault will only result in loss of supply to one substation, but supply cannot be restored here until the fault is located and repaired.

It should be noted that under cable fault conditions it would be necessary to disconnect the transformer in order to apply fault localisation tests to the cable. Disconnecting the cable may be considered rather inconvenient, and it is sometimes thought preferable to insert fault making, load breaking oil switches immediately prior to the transformer to give a ready means of isolation.

If this system is used for the distribution of power in a factory, it may also be thought preferable to use remote push-buttons for each transformer, which in emergency can be used to trip out the automatic circuit-breaker concerned in the primary substation. Whether this arrangement is economical is largely governed by the distances involved between the primary substation and each remote transformer.

A typical double-tier 440V, 31MVA class M23 air-break switchboard. Operator removing a circuit-breaker for maintenance by means of hydraulically operated handling truck.


'B' S/STN
'A' S/STN
PRIMARY SUBSTATION
BUS SECTION
'D' S/STN
LOAD
'C' S/STN
'F' S/STN
'E' S/STN

System 3

SYSTEM No. 4

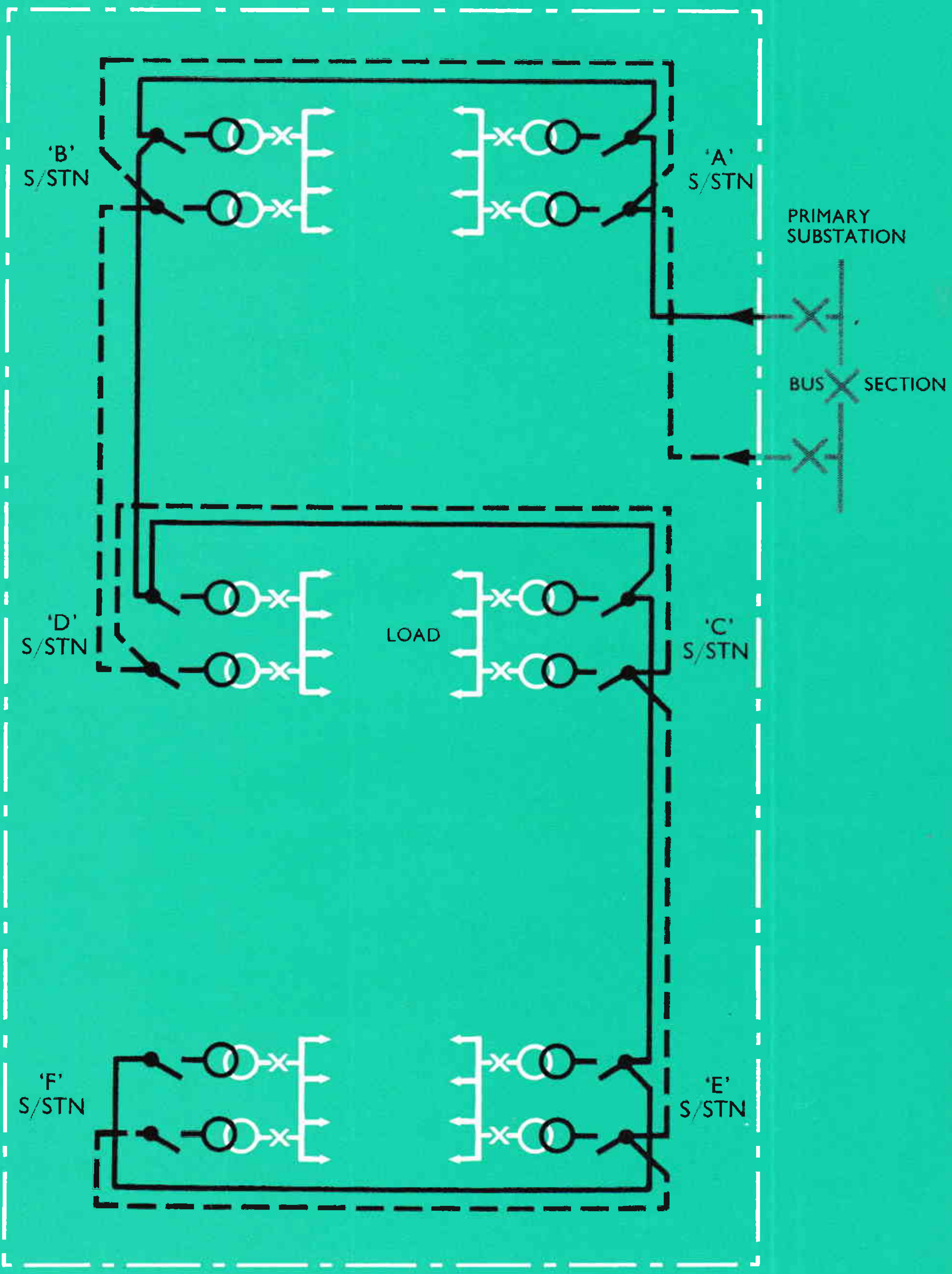
The primary substation has two outgoing feeders each controlled by an automatic circuit-breaker. At each distribution substation there is a duplication of transformers, each one being controlled by a fault making, load breaking oil switch. The system can be operated with the load equally divided with say substations 'A', 'B' and 'D' on one feeder, and substations 'C', 'E' and 'F' on the other.

Any individual transformer or medium voltage switchboard can be isolated for inspection and maintenance without any interruption of supply in the case of the transformer, and without interruption of supply to the other five substations in the case of a medium voltage switchboard.

Under these conditions a fault on any cable or transformer will result in loss of supply to three substations only, but after isolation of the fault, supply can be completely restored by means of the alternative feeder.

Another method of operating this system, if conditions in the primary substation permit, is by operating the two cables in parallel with all oil switches closed at each distribution substation. If on the medium-voltage side of each transformer there is an automatic circuit-breaker fitted with reverse-current protection, then a cable or transformer fault will not result in any loss of supply, since the automatic circuit-breaker in the primary substation will disconnect the 11,000 volt supply, and any feed back via transformers will be prevented by the associated medium-voltage circuit-breakers operating under the application of reverse-current protection.

'ENGLISH ELECTRIC' 500 kVA transformer being installed at the headquarters of the Institution of Electrical Engineers.


'B' S/STN
'A' S/STN
PRIMARY SUBSTATION
BUS SECTION
'D' S/STN
LOAD
'C' S/STN
'F' S/STN
'E' S/STN

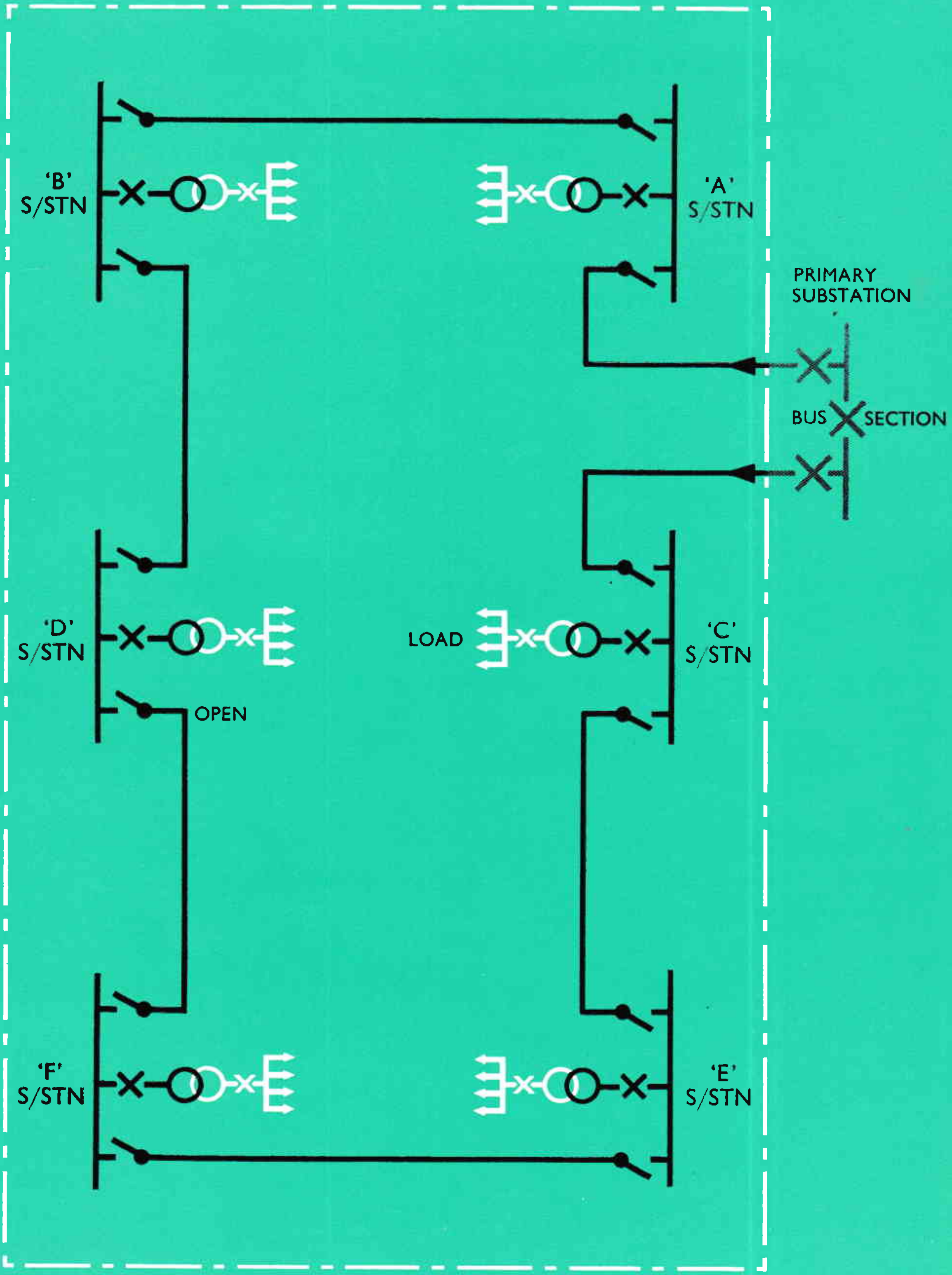
System 4

SYSTEM No. 5

Two outgoing feeders from the primary substation are each controlled by an automatic circuit-breaker, with the feeders arranged in the form of a ring with a dividing point, at say, substation 'D', so that each feeder is equally loaded. At each distribution substation the incoming and outgoing cables are controlled by oil switches, and each transformer by an automatic circuit-breaker ; thus, every transformer and medium voltage switchboard is entirely independent of the rest of the system.

With this arrangement a cable fault would result in the loss of supply to three substations, but supply can be completely restored after isolation of the faulty section. A transformer fault would be cleared by the appropriate automatic circuit-breaker controlling it, thus leaving the remainder of the system entirely unaffected.

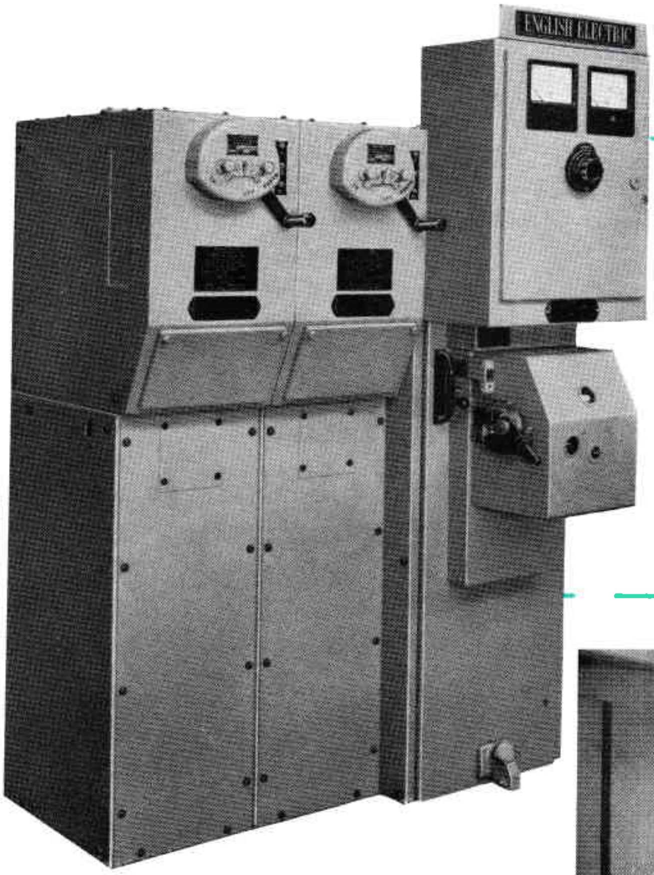
Switchboard comprising hand operated OLX oil circuit-breakers and independent manual spring-close oil switches.


'B' S/STN
'A' S/STN
PRIMARY SUBSTATION
BUS SECTION
'D' S/STN
LOAD
'C' S/STN
OPEN
'F' S/STN
'E' S/STN

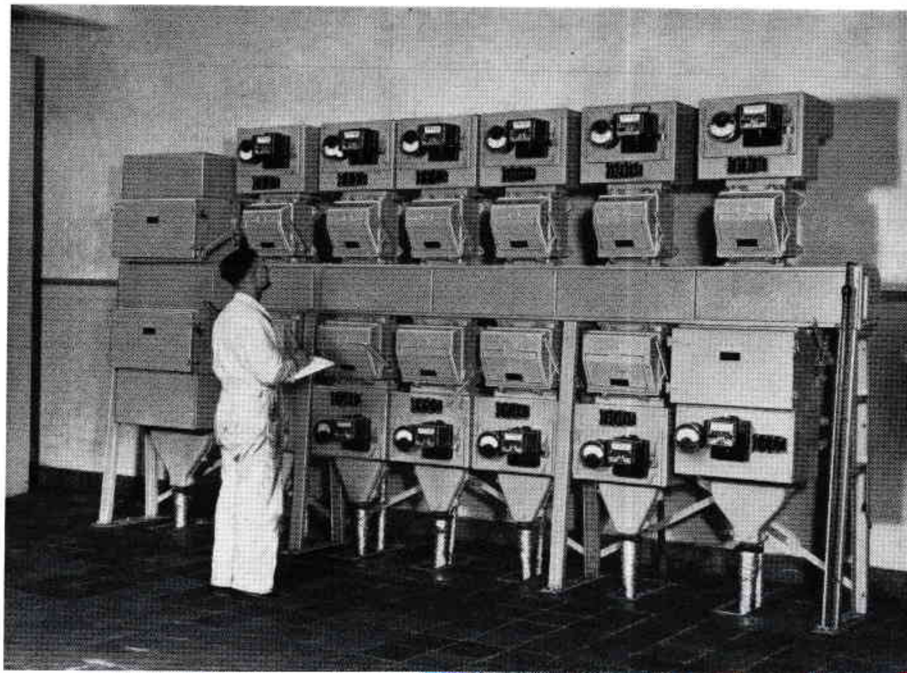
System 5

SYSTEM No. 6

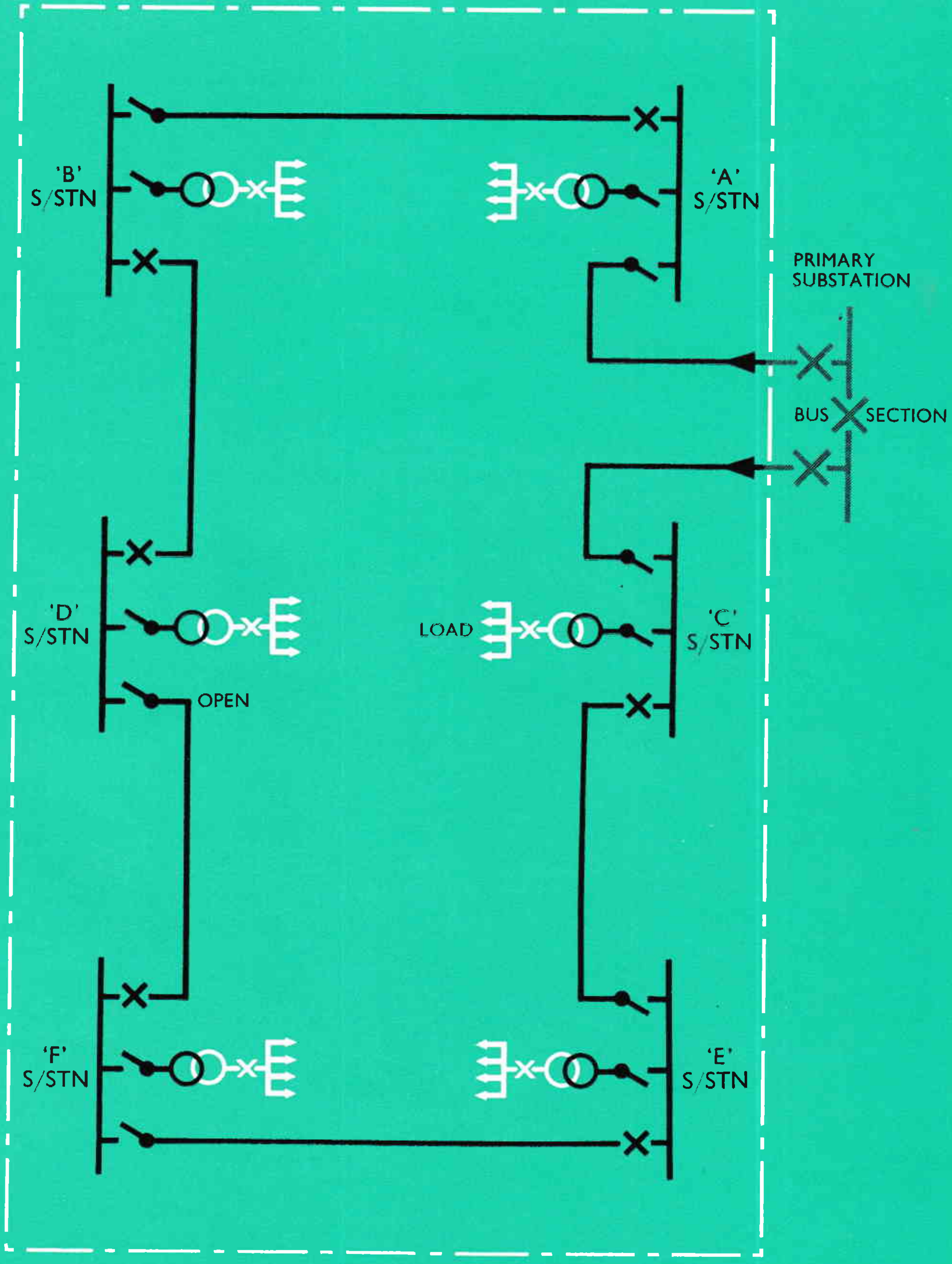
This utilises exactly the same equipment as System No. 5, but in a slightly rearranged form. The automatic circuit-breaker at each distribution substation is utilised to protect a section of cable in addition to a transformer. The opportunity is, therefore, available for using time-graded protection and securing a reduction in the loss of supply under cable fault conditions.



OLX ring main unit with spring-operated oil circuit-breaker and two manually-operated oil switches mounted on one side.



Combination fuse-switchboard in industrial premises.

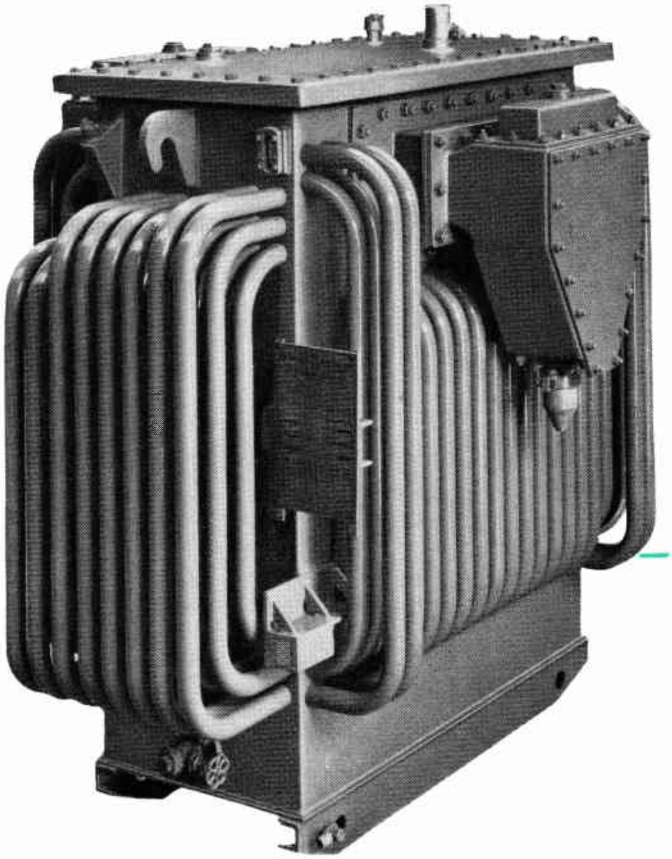

'B' S/STN
'A' S/STN
PRIMARY SUBSTATION
BUS SECTION
'D' S/STN
LOAD
'C' S/STN
OPEN
'F' S/STN
'E' S/STN

System 6

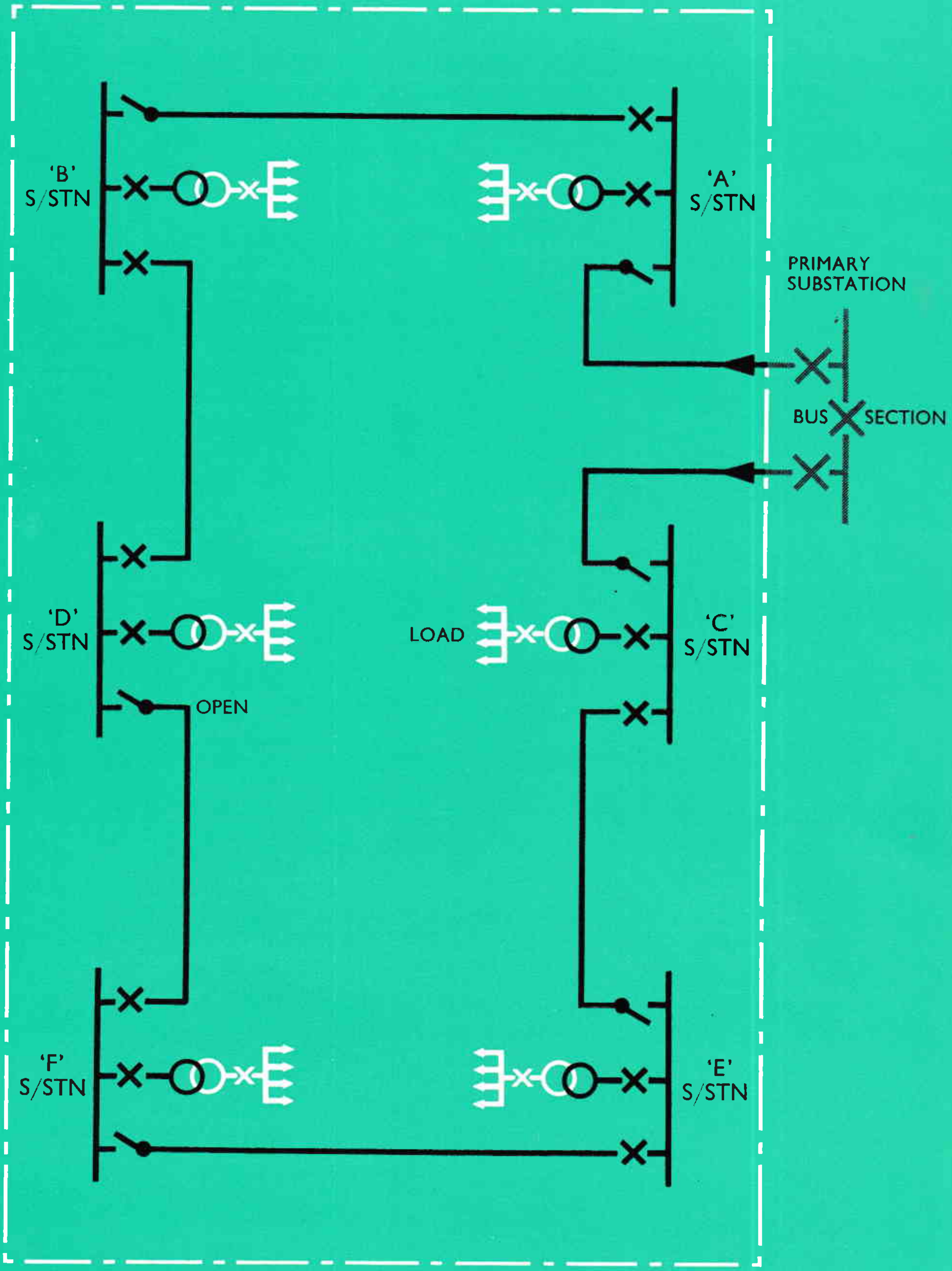
SYSTEM No. 7

This is exactly the same as System No. 5, with the exception that an automatic circuit-breaker is used to control each outgoing feeder instead of an oil switch. This means that time-graded protection can be used with a consequent reduction in the amount of plant shut down due to a cable fault. For example, if a fault should develop on the cable between 'B' and 'D' substations, then the automatic circuit-breaker at 'B' substation will open, so that the only supply loss will be that to 'D' substation. Supply to the latter can, of course, be resumed by isolating the faulty cable section and closing the alternative supply. Similarly, a cable fault between 'A' and 'B' substations will result in the opening of the automatic circuit-breaker in 'A' substation with a consequent loss of supply to 'B' and 'D' substations. Supply can be resumed to 'B' and 'D' by isolating the faulty cable section and feeding back in the opposite direction by closing in at 'D' substation.

One disadvantage of this system is that the system protection is not correct under the latter abnormal conditions, and will result in the disconnection of more substations than strictly necessary should a further cable fault develop. This can perhaps be illustrated more clearly by supposing that the cable between the primary substation and 'A' substation is out of commission for some reason ; then referring to 'B' substation the incoming supply is now controlled by an automatic circuit-breaker, and the outgoing supply controlled by an oil switch, due to the reversing of the feeding arrangements. With this latter condition, therefore, a fault on the cable between 'A' and 'B' substations would mean the loss of both due to the opening of the feeder circuit-breaker at 'B' substation.



300 kVA substation transformer complying with the British Electricity Board's Specification T.1.

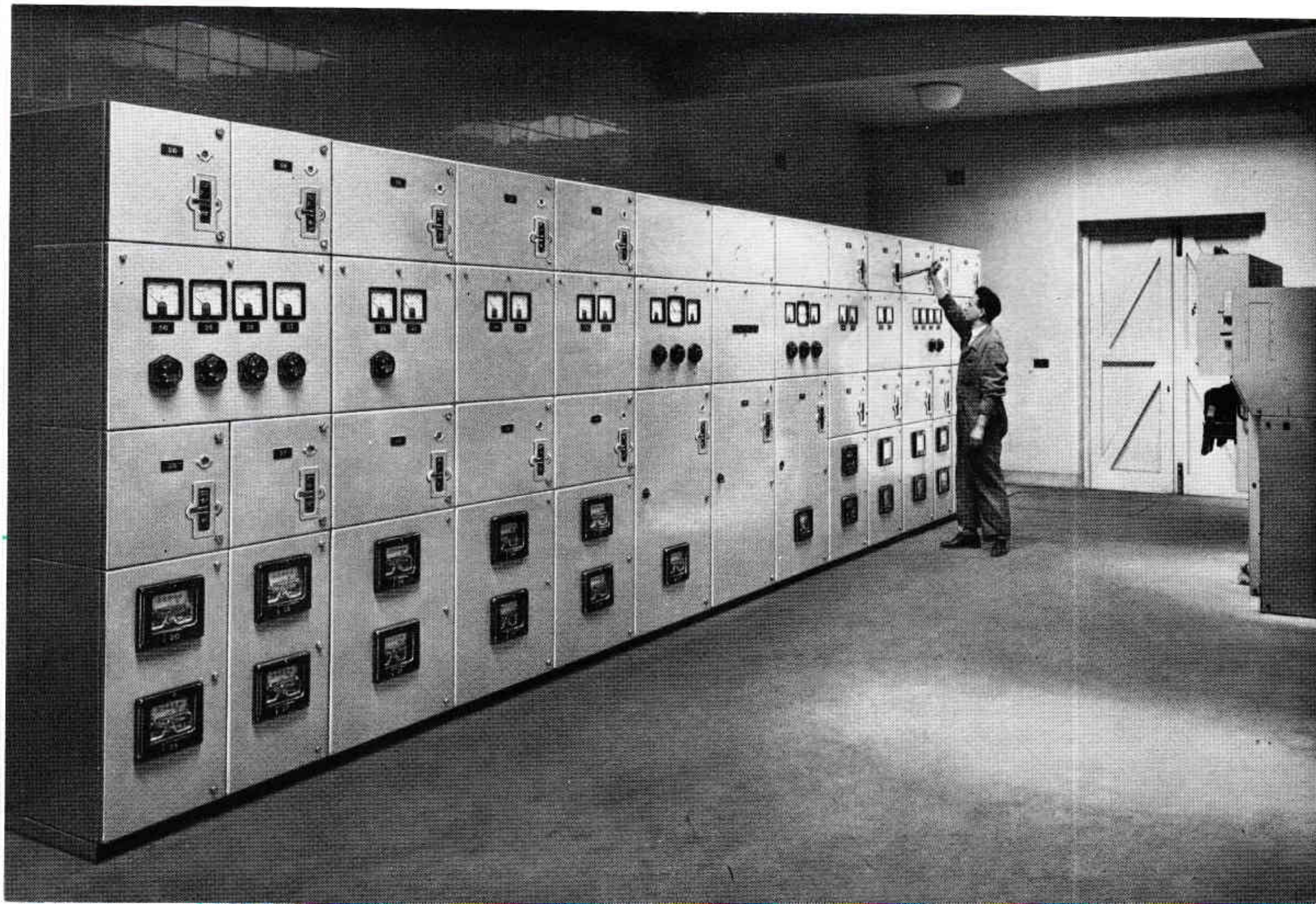

'B' S/STN
'A' S/STN
PRIMARY SUBSTATION
BUS SECTION
'D' S/STN
LOAD
'C' S/STN
OPEN
'F' S/STN
'E' S/STN

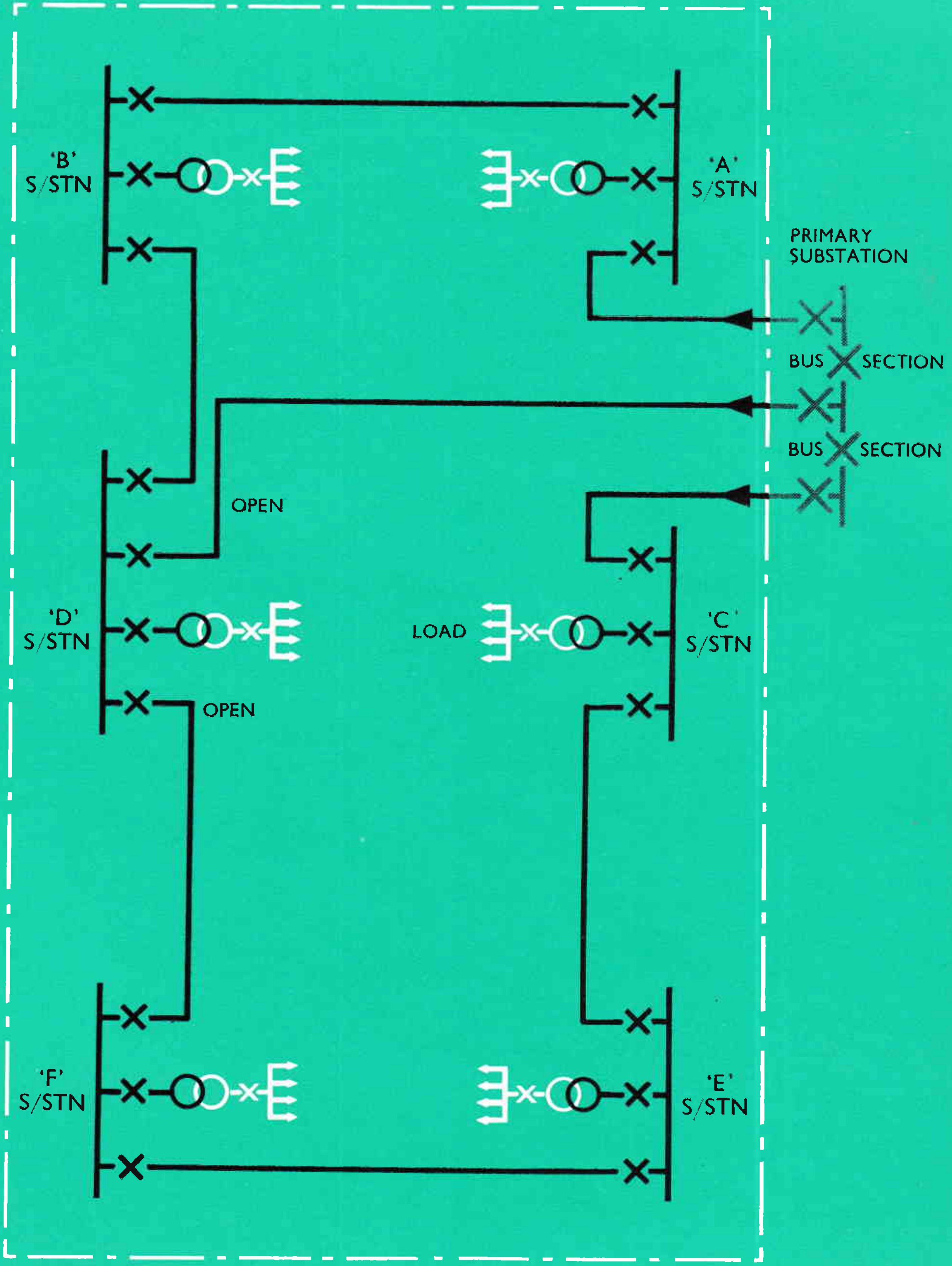
System 7

SYSTEM No. 8

In this system automatic circuit-breakers are used throughout, thus eliminating any difficulties due to the reversing of feeding arrangements. In the primary substation the busbars are sectionalised by means of bus-section switches with three outgoing feeders to the network. Two of these feeders form a complete ring as in System No. 7, whilst the third is taken to the centre of the ring to provide additional security of supply. The use of this third feeder means that the cable sizes for the primary ring can be reduced whilst still maintaining the ability to give full duplication of supply. The ring could be normally divided at, say, 'D' substation, and the use of automatic circuit-breakers throughout permits time-graded protection regardless of the direction of the feeding arrangements at any particular time. A cable fault would be cleared without any interruption of supply.

Modern industrial substation equipped with an 'ENGLISH ELECTRIC' 'Superform' MV distribution switchboard and type OLX H.V. switchgear.

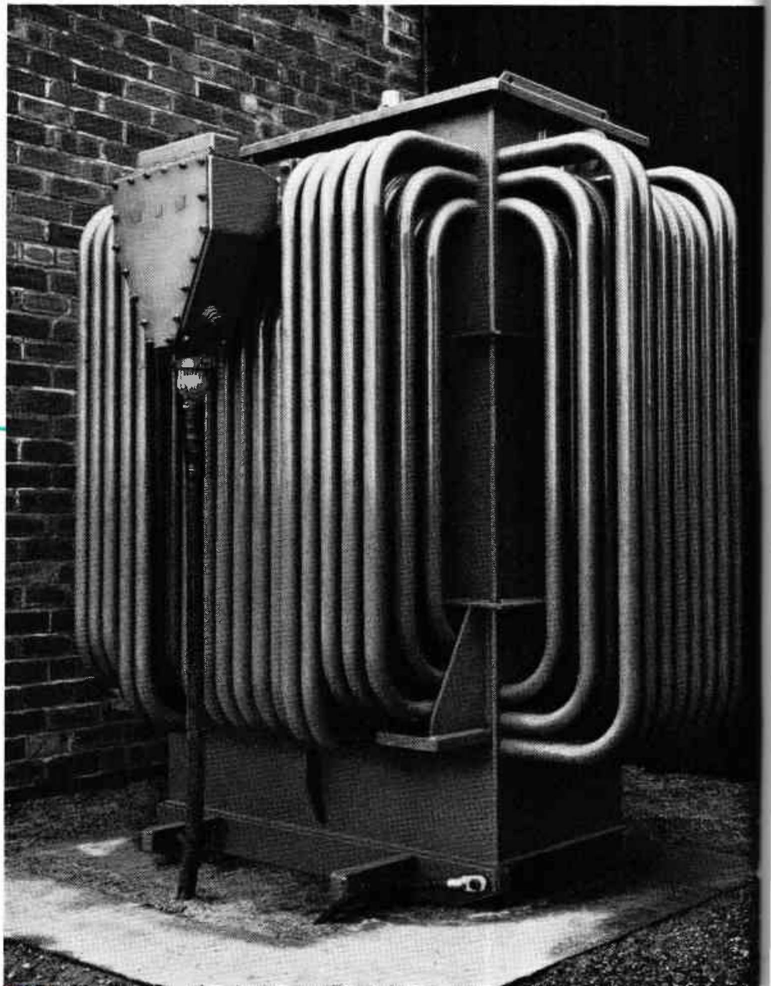


'B' S/STN
'A' S/STN
PRIMARY SUBSTATION
BUS SECTION
BUS SECTION
OPEN
'D' S/STN
LOAD
'C' S/STN
OPEN
'F' S/STN
'E' S/STN

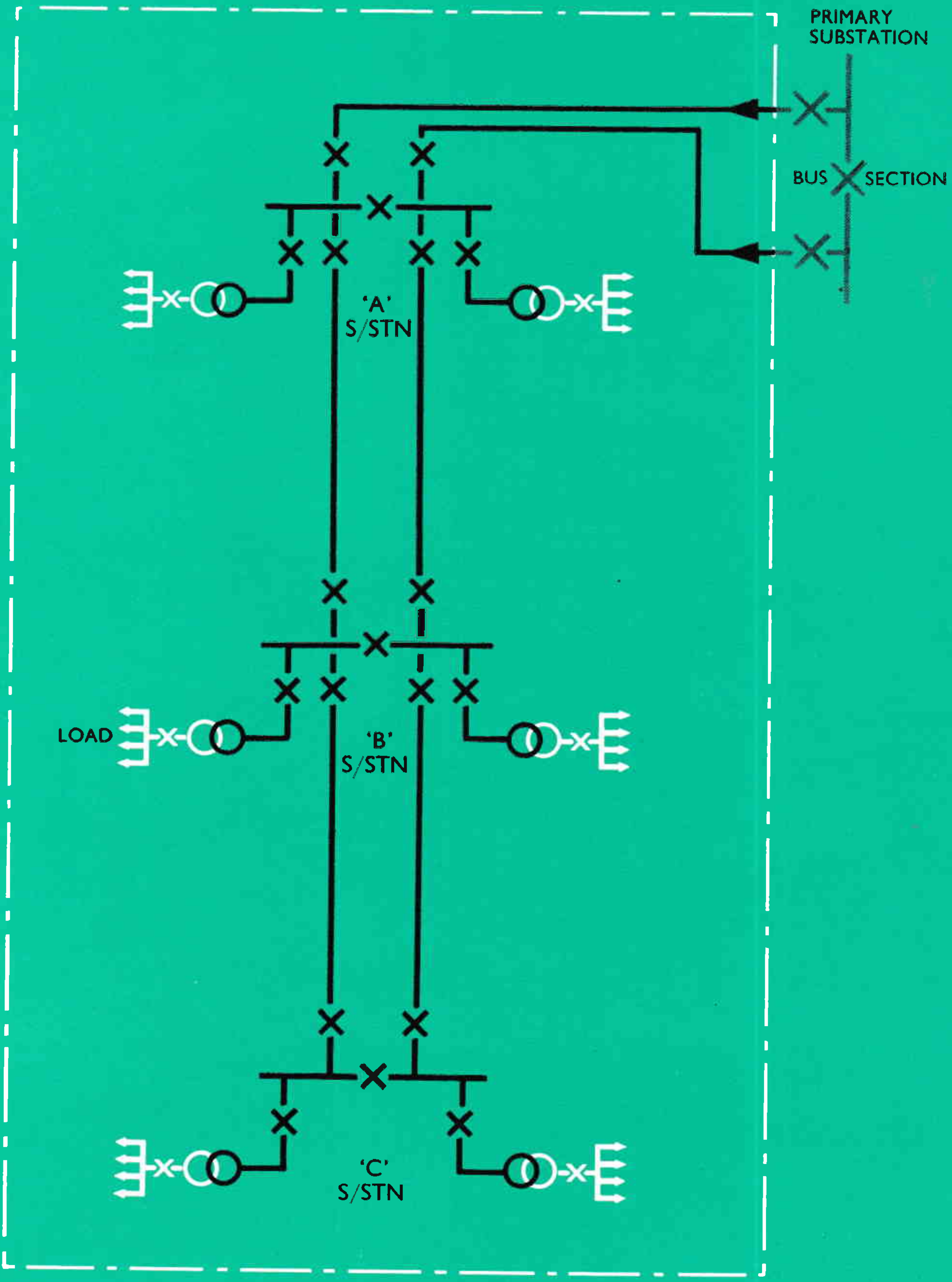
System 8

SYSTEM No. 9

The primary substation has two outgoing feeders to three distribution substations 'A', 'B' and 'C'. Each substation has two sets of busbars which may be joined together by means of a bus-section switch, and if conditions permit, all bus-section switches can operate in the normally-closed position. By the application of parallel feeder protection, it is possible to arrange that there shall be no interruption of supply for a cable fault, since the faulty section will be automatically disconnected at each end under fault conditions. If the two feeder cables must be operated separately, then all bus-section switches must be in the normally-open position. Under these conditions time-graded protection can be used, thus minimising the extent of the interruption to supply upon the occurrence of a fault, and retaining full duplication of supply as an alternative feeding arrangement.



'ENGLISH ELECTRIC' 1,000 *kVA transformer installed at an industrial power station.*



System 9

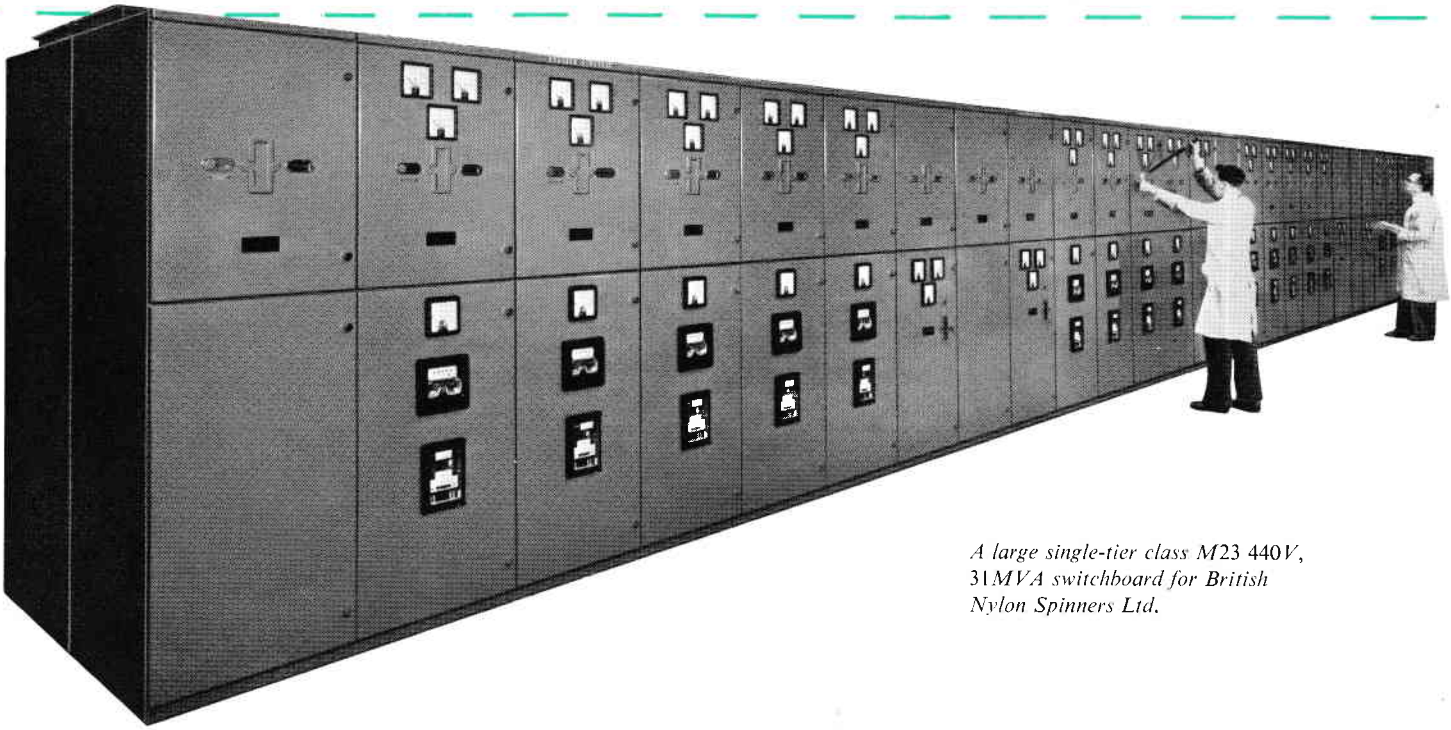
SYSTEM No. 10

This system uses automatic circuit-breakers throughout and is again designed on the ring principle, after the manner of Systems Nos. 7 and 8.

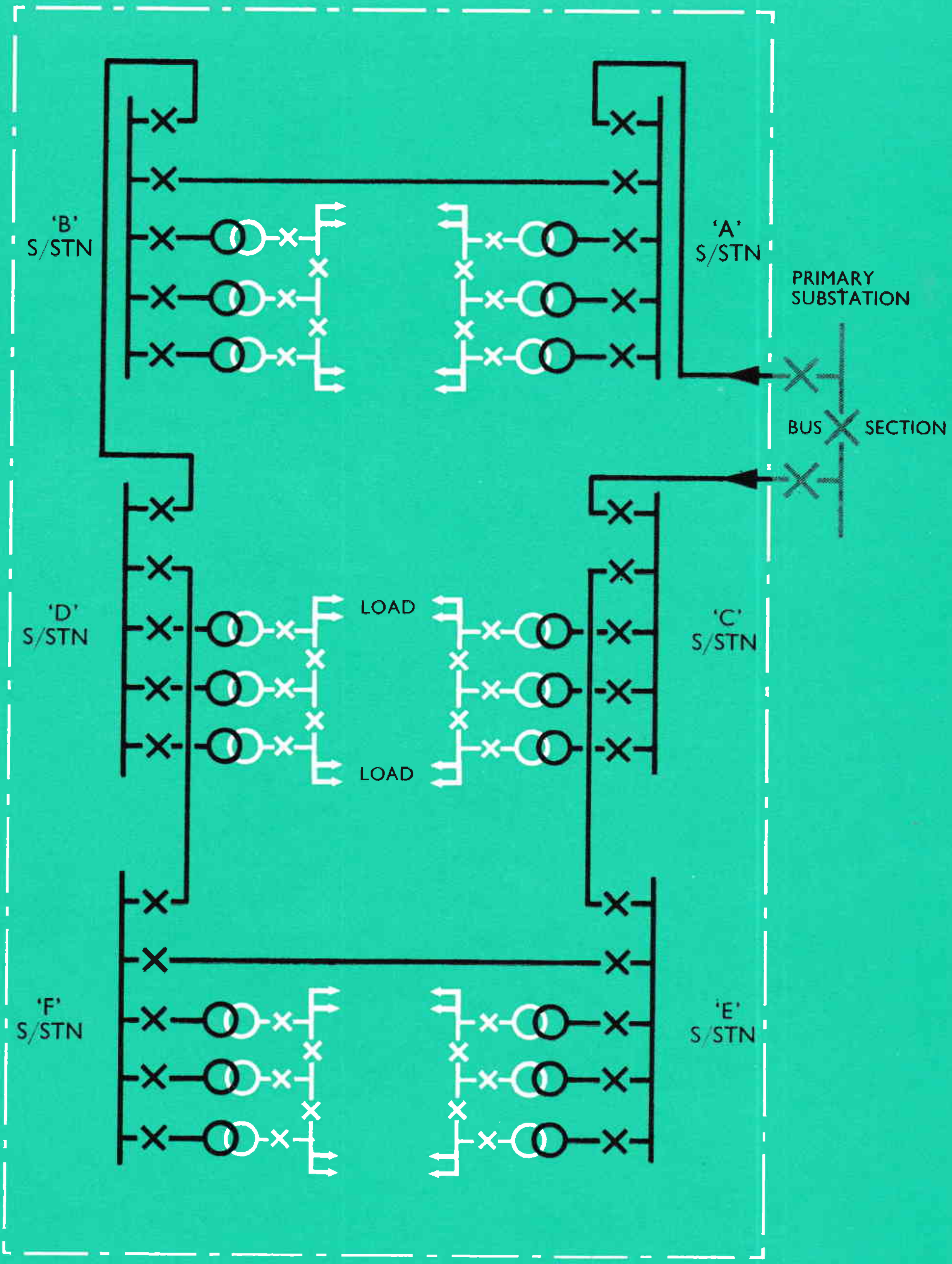
If conditions permit, the system may be operated as a closed ring, and under these circumstances each section of the cable making up a ring could be individually protected by using some form of balanced current protection, possibly with associated pilot cable, thus ensuring that when a cable fault occurs the protection will disconnect the faulty section at each end without any loss of supply.

If conditions in the primary substation are against the system being operated as a closed ring then it will be necessary to have a dividing line, at say, 'D' substation, so that each outgoing feeder is equally loaded, and in this instance time-graded protection would normally be used.

As a further guarantee against loss of supply due to say a transformer fault, several transformers are installed at each distribution substation thus ensuring that there is sufficient spare capacity available should one transformer be lost on fault.



A large single-tier class M23 440V, 31MVA switchboard for British Nylon Spinners Ltd.


'B' S/STN
'A' S/STN
PRIMARY SUBSTATION
BUS SECTION
LOAD
'D' S/STN
'C' S/STN
LOAD
'F' S/STN
'E' S/STN

System 10

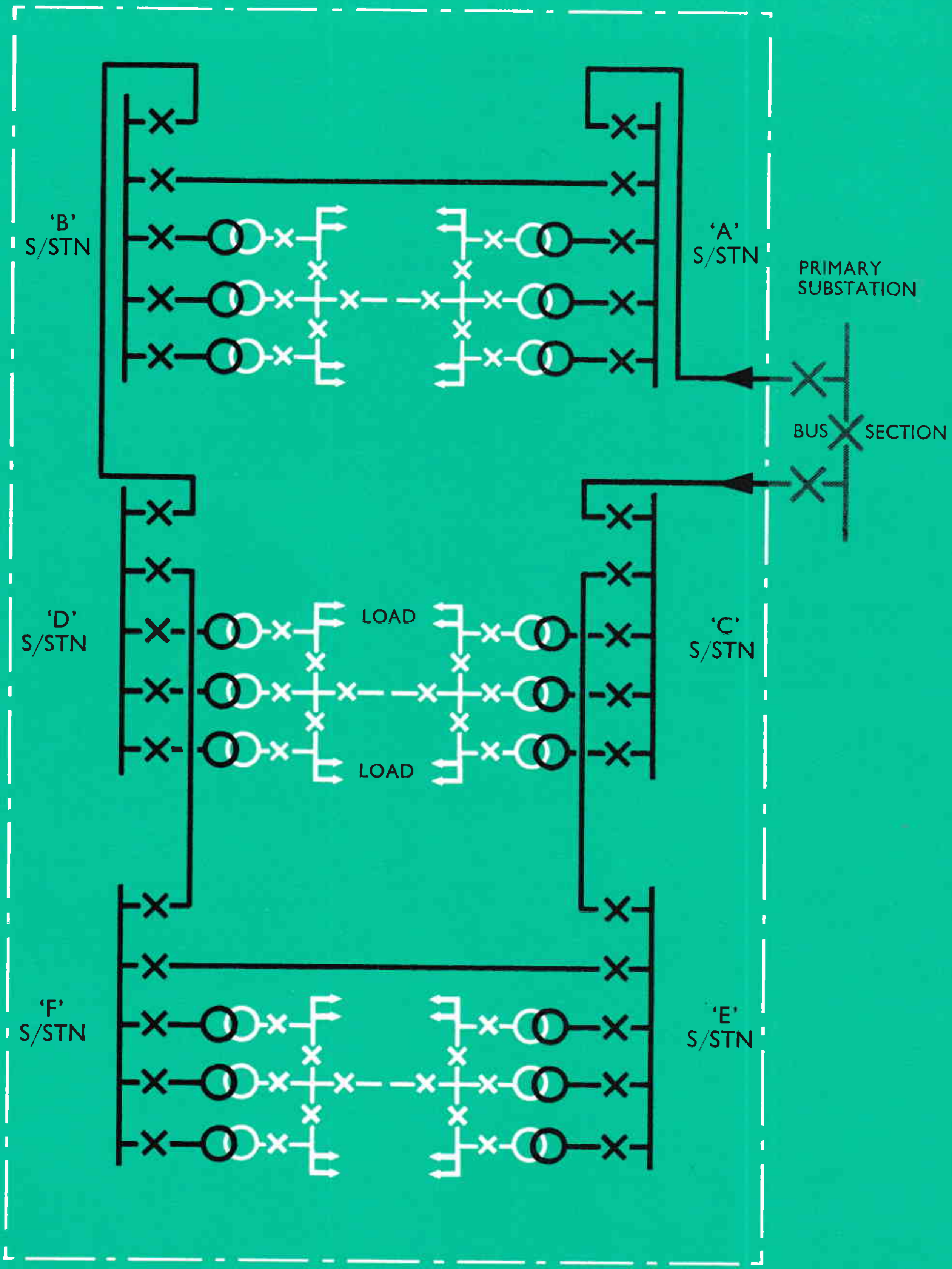
SYSTEM No. 11

In none of the previous systems has the question of medium-voltage interconnections between substations been considered. The use of such interconnection will, of course, provide some alternative source of supply in all systems, with the exception of system No. 1, under cable fault conditions. Its use will depend upon having spare transformer capacity available at each substation so interconnected, and it is necessary to consider the lengths and sizes of the cables involved, particularly with reference to voltage drop which is much more critical at this voltage.

This system, therefore, is identical to system No. 10, with the addition of medium-voltage interconnection between substations 'A' to 'B', 'C' to 'D', and 'E' to 'F'.

This medium-voltage interconnection also permits the transformers to be disconnected for inspection and maintenance whilst retaining supply via the interconnector. From the safety point of view, it is necessary to pay particular attention to the possibility of feed back from the medium-voltage network in order to avoid danger to personnel.

A compound-insulated class CV high-voltage oil-break switchboard arranged for manual closing.


'B' S/STN
'A' S/STN
PRIMARY SUBSTATION
BUS SECTION
'D' S/STN
LOAD
LOAD
'C' S/STN
'F' S/STN
'E' S/STN

System 11

APPENDICES

APPENDIX I

(For very accurate calculations, actual values should be obtained from a cable manufacturer)

APPROXIMATE RESISTANCE AND REACTANCE OF COPPER MULTICORE CABLES

Conductor Size sq. ins.	Resistance per 1000 yds. ohms	REACTANCE IN OHMS PER 1000 YDS. (AT 50 c/s)			
		415V system 3 or 4 core	3·3 kV system 3 core	6·6 kV system 3 core	11 kV system 3 core (belted)
0·0225	1·15	0·080	0·087	0·094	0·104
0·04	0·642	0·073	0·079	0·085	0·093
0·06	0·424	0·070	0·076	0·080	0·088
0·10	0·252	0·067	0·072	0·076	0·082
0·15	0·172	0·064	0·068	0·071	0·076
0·20	0·130	0·063	0·066	0·070	0·074
0·25	0·103	0·062	0·065	0·068	0·072
0·30	0·084	0·062	0·064	0·067	0·071

NOTE. The resistance values are for the cable at 20°C. and should be used for fault calculations. When the cable is at full load temperature, the resistance values will be increased by 20–24%.

APPENDIX II

TYPICAL 'ENGLISH ELECTRIC' 3-PHASE TRANSFORMER CHARACTERISTICS (COLD-ROLLED-STEEL CORES) COMPLYING WITH BRITISH ELECTRICITY BOARD'S SPECIFICATION T.1. (1954)

Voltage Ratio	Capacity kVA	Iron Loss. watts	Copper Loss. watts at 75°C.	Impedance % at 75°C.	Reactance % at 75°C.
3,300/433—250	100	333	1,900	4·75	4·35
	200	580	3,230		4·46
	300	848	4,370		4·52
	500	1,282	6,517		4·56
	750	1,816	9,025		4·6
	1,000	2,299	11,229		4·61
6,600/433—250 and 11,000/433—250	25	137	665	4·5	3·63
	50	212	1,121		3·9
	100	359	1,900	4·75	4·35
	200	605	3,230		4·46
	300	892	4,370		4·52
	500	1,336	6,517		4·56
	750	1,843	9,025		4·6
	1,000	2,299	11,229		4·61

'ENGLISH ELECTRIC' CIRCUIT-BREAKERS TO B.S.116

Service Voltage kV	Breaking Capacity MVA	Circuit-breaker Type	Type of Break	Breaking Current kA		Making Current Peak kA	Normal Current Rating up to Amp.
				Symmetrical	Asymmetrical		
0·415	5·2	OLA. 1	Oil	7·24	8·85	18·4	300
	5·2	OLA. 2	Oil	7·24	8·85	18·4	600
	15·6	OB2	Air	21·6	26·3	55	600
	31·0	OB23	Air	43·3	53·1	110·5	800/1200/1600
	31·0	OB24	Air	43·3	53·1	110·5	3000
3·3	25	OLA. 1	Oil	4·38	5·37	11·2	150
	25	OLA. 2	Oil	4·38	5·37	11·2	400
	75	OLX, CV	Oil	13·1	16·1	33·4	1200
	100	OLX, CV	Oil	17·5	21·5	44·6	1200
	150	OLX, CV	Oil	26·3	32·2	67·0	1200
	150	OB33L	Air	26·3	32·2	67·0	2000
	250	E4, OB50	Air	43·8	53·7	112·0	2000
6·6	75	OLX, CV	Oil	6·57	8·05	16·7	1200
	100	OLX, CV	Oil	8·76	10·75	22·3	1200
	150	OLX, CV	Oil	13·1	16·1	33·4	1200
	250	OLX, CV	Oil	21·9	26·8	55·8	1200
	250	E5	Air	21·9	26·8	55·8	2000
	250	E6	Air	21·9	26·8	55·8	3000
	350	E5	Air	30·6	37·5	78·0	2000
	350	E6	Air	30·6	37·5	78·0	3000
11	75	OLX, CV	Oil	3·94	4·83	10·1	1200
	100	OLX, CV	Oil	5·25	6·43	13·4	1200
	150	OLX, CV	Oil	7·88	9·65	20·1	1200
	250	OLX, CV	Oil	13·1	16·1	33·4	1200
	350	OLX	Oil	18·4	22·6	47·0	1200
	500	E5	Air	26·2	32·2	66·8	2000
	500	E7	Air	—	—	—	Projected

SWITCHES AND ISOLATORS TO B.S.S.

Service Voltage kV	Equivalent Short-circuit Rating — MVA	Switch Type	Type of Break	Breaking Current Amp.	Short Time Current kA	Making Current Peak kA	Normal Current Rating up to Amp.
0·415	31	OCE	Air	Off-load operation	43·3 R.M.S.	—	3000
6·6	150	OLX	Oil	400		33·4	400
	250	OLX	Oil	400		55·8	400
11	150	OLX	Oil	400		20·1	400
	250	OLX	Oil	400		33·4	400

NOTE:

OLX Oil Switch complies with B.S.2631: 1955.

OCE Switch: Through currents are in accordance with B.S.116.

'ENGLISH ELECTRIC'

BRANCH OFFICES THROUGHOUT THE UNITED KINGDOM

BEDFORD. Westminster Bank Chambers, High Street. Telegraph : "Enelectico, Bedford". Telephone : Bedford 67827/8.

BELFAST. 41 Donegall Place. Telegraph : "Enelectico, Belfast". Telephone : Belfast 31185.

BIRMINGHAM. Pitmaston, Moor Green Lane, Birmingham 13. Telegraph : "Enelectico, Birmingham 13". Telephone : South 4021/5.

BLACKBURN. 32 Preston New Road. Telegraph : "Enelectico, Blackburn". Telephone : Blackburn 44081/2.

BRISTOL. 36/38 Baldwin Street, Bristol 1. Telegraph : "Enelectico, Bristol". Telephone : Bristol 27304.

CARDIFF. St. David's House, Wood Street. Telegraph : "Enelectico, Cardiff". Telephone : Cardiff 25231/3.

EDINBURGH. Victoria Chambers, 42 Frederick Street, Edinburgh 2. Telegraph : "Enelectico, Edinburgh". Telephone : Caledonian 1645/6.

GLASGOW. 200 St. Vincent Street, Glasgow C.2. Telegraph : "Enelectico, Glasgow". Telephone : Central 4901/4.

HULL. Barclays Bank Chambers, 3 Trinity House Lane, Hull. Telegraph : "Enelectico, Hull". Telephone : Central 35533.

IPSWICH. 32 Queen Street, Ipswich. Telegraph : "Enelectico, Ipswich". Telephone : Ipswich 54489 and 54480.

LEEDS. Darley House, St. Paul's Street, Leeds 1. Telegraph : "Enelectico, Leeds". Telephone : Leeds 20556/9.

LEICESTER. Halford House, Charles Street. Telegraph : "Enelectico, Leicester". Telephone : Leicester 24775/6.

LIVERPOOL. India Buildings, Water Street, Liverpool 2. Telephone : Liverpool Central 7451/5.

LONDON. English Electric House, Strand. Telegraph : "Enelectico, Estrand, London". Telephone : Covent Garden 1234.

MANCHESTER. English Electric House, Crossford Court, Dane Road, Sale, Cheshire. Telegraph : "Enelectico, Manchester, Telex". Telephone : Sale 8211/7.

MIDDLESBROUGH. 89 Albert Road. Telegraph : "Enelectico, Middlesbrough". Telephone: Middlesbrough 44346/7.

NEWCASTLE-ON-TYNE. Marconi House, Melbourne Street, Newcastle-on-Tyne. Telegraph : "Enelectico, Newcastle". Telephone : Newcastle 23034/5.

SHEFFIELD. Norwich Union Buildings, 22 High Street, Sheffield 1. Telegraph : "Enelectico, Sheffield 1". Telephone : Sheffield 22251/3.

SLOUGH. 9 Mackenzie Street, Slough. Telegraph : "Enelectico, Slough". Telephone : Slough 24587/8.

SOUTHAMPTON. 29 Shirley Road. Telegraph : "Enelectico, Southampton". Telephone : Southampton 28222/3.

STOKE-ON-TRENT. Federation House, Station Road. Telegraph : use telephone number. Telephone : Stoke-on-Trent 47182 and 47592.

SWANSEA. 13 College Street, Swansea. Telegraph : "Enelectico, Swansea". Telephone : Swansea 50502/3.

TONBRIDGE. 111 High Street. Telegraph : "Enelectico, Tonbridge". Telephone : Tonbridge 2704.

WOLVERHAMPTON. Lloyds Bank Chambers, Chapel Ash. Telegraph : "Enelectico, Wolverhampton". Telephone : Wolverhampton 25476/7.

'ENGLISH ELECTRIC'

Switchgear Department · East Lancashire Road, Liverpool 10. Tel. AINtree 3641

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Publication SG/338A (Superseding Publn. SG/338) *Printed in England* 016425BW/RP0362